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New York University
Constant Level Balloons
Section 1, *General*
November 15, 1949

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CONSTANT LEVEL BALLOONS
Section 1

GENERAL

Constant Level Balloon Project
New York University

Prepared in accordance with provisions of contract
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Watson Laboratories, Red Bank, New Jersey
and
New York University

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I. INTRODUCTION

A. Contract Requirements

On November 1, 1946 the Research Division of the College of Engineering of New York University entered into Contract W28-099-ac-241 with Watson Laboratories of the Air Materiel Command. Under this contract the University was commissioned to design, develop and fly constant-level balloons to carry instruments to altitudes from 10 to 20 kilometers, adjustable at 2-kilometer intervals.

The following performance was specified:

1. Altitude to be maintained within 500 meters.

2. Duration of constant level flight to be initially 6 to 8 hours minimum, eventually 48 hours.

3. The accuracy of pressure observation to be comparable to that obtainable with the standard Army radiosonde ($\pm$3-5 mb).

In addition to this balloon performance it was desired that:

4. A balloon-borne transmitter be developed for telemetering of information from the balloon to suitable ground receivers.

5. Positioning of balloon during flight be determined by ground tracking such as radar or radio direction-finding or theodolite.

6. Appropriate meteorological data be collected and interpreted.

Following the first year of work the contract was renewed for a 1-year period, and in addition to the provisions of the original contract it was agreed that a total of 100 test flights would be launched by the University.

In September, 1948 a second renewal of the contract was effected. With this renewal, which expires in March, 1949, it is expected that the development of equipment will be concluded. Further extensions are under consideration whereby New York University will supply standardized flight gear and flight service personnel for routine test flights.

B. Project Facilities

To meet the requirements of the contract, a research group was built up and the following facilities were made available:

1. Administrative section.

2. Engineering personnel were assigned to one or more of the following groups:

   (a) Balloon section
   (b) Performance control section
   (c) Telemetering section
   (d) Analysis section (including meteorological and performance data analysis)

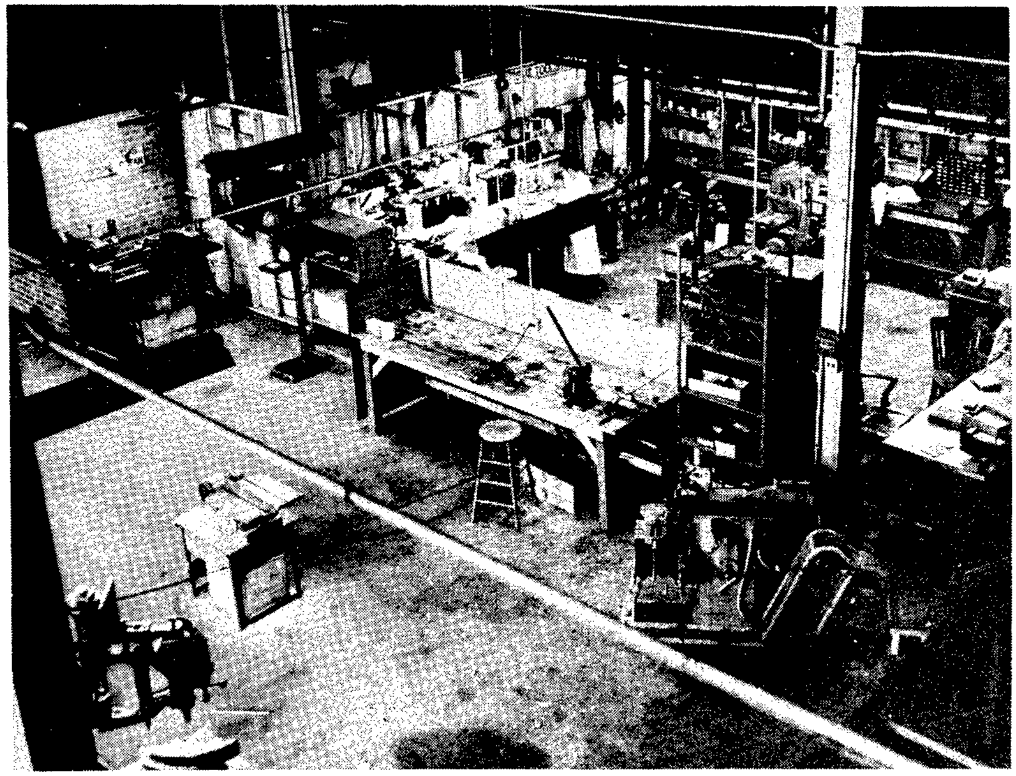
3. A small machine shop was provided to manufacture experimental models of equipment which was flown.

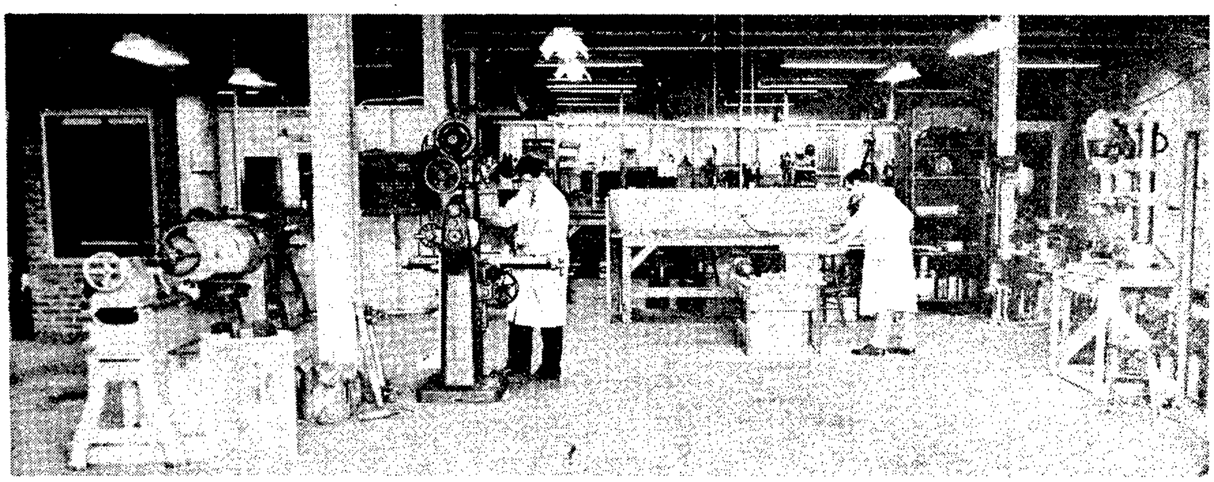
4. A field crew for launching, tracking and recovery of balloons was established.

Work-shop, laboratory, office and storage space was provided by New York University (Figures 1 and 2). Field work was largely conducted at Army bases and Air Forces installations. At one time the number of full-time employees reached 26 with 17 part-time men on the staff at that time. Most individuals were called upon to work in several departments depending upon the urgency of field work, equipment preparation or development work.

II. PRINCIPLES OF BALLOON CONTROL

Following preliminary investigations, two distinct principles of achieving constant-pressure altitude for free balloons were studied in detail. The first of these is the maintenance of the balloon at floating level by the use of a servo-mechanism or other control which causes the supported load to vary with the buoyancy of the balloon. The second principle embodies the use of a non-extensible balloon capable of withstanding a high internal pressure. With a fixed volume and a given load, such balloons remain at a constant pressure level as long as the internal pressure of the balloon is equal to or greater than that of the air at floating level. A surplus of buoyancy causes super-pressure, but when the gas is cooled relative to the air environment such a surplus is needed to prevent excessive reductions in balloon pressure. Whenever the balloon's internal pressure becomes less than that of the air, it falls to earth. Such a balloon was used by the Japanese for the fire bombing of the western United States during World War II.





Figures 1 and 2. Interior views, Research Division Shop.

To use the first of these principles it is possible to maintain a condition of buoyancy by at least the following two methods: (1) dropping a part of the load, as ballast, to match the loss of lifting gas which occurs as a result of diffusion and leakage; (2) replacement of the lifting gas by evaporation from a reservoir of liquified helium or hydrogen. Of these two methods, ballast dropping is most satisfactory from the consideration of simplicity of control and safety of personnel. While the use of liquid helium is theoretically more efficient, the amount and complexity of control equipment adds much to the cost and also the weight of air-borne equipment.

The development of non-elastic balloons which can withstand high internal pressure was investigated. Two designs which compromise extreme cost (required for balloons of high internal pressure) with small wall strength, hence small super pressure, were tested.

At first, attempts were made to control balloon performance by using buoyancy-load balance techniques with elastic balloons, but the difficulties which were experienced resulted in the development of a third principle of operation combining a non-extensible balloon with a system of controls which can be applied either to a freely expanding balloon or to a balloon of fixed volume.

III. METHODS OF ATTACK

The work on the development of controlled-altitude balloons may be divided into three phases, each one identified by the type of balloon which was used. Concurrent with the balloon development was the design and testing of control equipment required to maintain the balloon at specific altitudes. Some of the equipment instrumentation was used on more than one kind of balloon, but in general the problems and methods of attack are identified with one of the three types of balloons.

A. Rubber Balloons

Following the example of Clarke and Korff, assemblies of neoprene rubber balloons were first considered. Using these freely expanding balloons it was necessary to balance the load to be lifted with the buoyancy given by an integral number of balloons. One or more accessory balloons were attached to the assembly to provide lifting force to carry the train aloft. With the gear at a predetermined altitude, the lifting balloons were cut loose from the train by a pressure-activated switch, leaving the equipment at floating level, more or less exactly balanced. Since there is no inherent stability in an extensible balloon, any existing unbalance will cause the train to rise or fall indefinitely until the balloon reaches its bursting diameter, the gear strikes the ground, or corrective action is taken. Even if the extremely critical balance is initially achieved, there will be unbalance occasioned by (1) bursting of balloons due to deterioration in the sunlight, (2) diffusion of lifting gas from the balloons, (3) loss or gain of buoyancy when temperature inside the balloon changes with respect to the ambient air temperature. This will result initially from radiative differences, and after an amount of difference (superheat) has been established, changes in ventilation will cause changes in buoyancy.

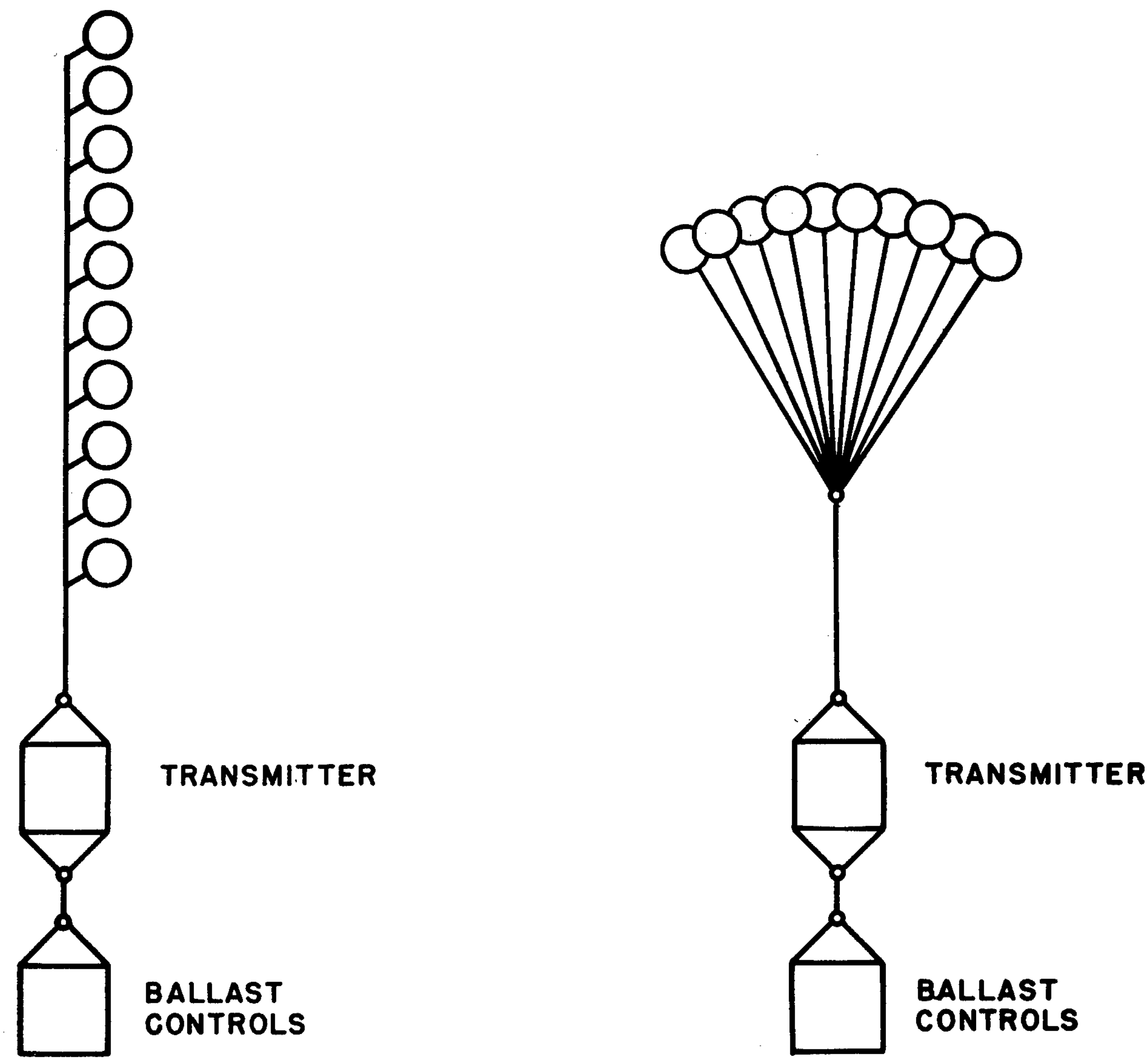
Two methods of attaching the payload to the clusters of rubber balloons were tried. In the first of these (Figure 3) a long load line was used, and short lines led from it to the individual balloons. The length of such arrays was as much as 800 feet, and this size made them difficult to launch. The single load ring array, seen in Figure 4, proved to be much easier to handle and is recommended for cluster launchings. During ascent each of the balloons in such an array ride separated from each other and no rubbing or chafing has been observed.

The controls which were associated with this balloon system were crude and, in general, ineffective. They included (1) cutting off balloons as the buoyancy became excessive and a preset altitude extreme was passed, and (2) releasing part of the load in the form of solid or liquid ballast whenever descent occurred. The sensitivity of these elastic balloons makes it difficult to control their altitude with any system of controls, and as controls were developed it was found more practical to change from freely expanding balloons to non-extensible cells not made of neoprene. The tendency of neoprene to decay within a few hours when exposed to sunlight was the most cogent argument against doing more work on altitude controls to be used with such a system.

B. Plastic Balloons

The next attempts to control the altitude of a balloon vehicle were made using non-extensible plastic cells, with an open bottom to prevent rupture when expansion of the lifting gas is excessive. With a fixed maximum volume, such a system has inherent vertical instability in only one direction. When full, there is a pressure altitude above which a given load will not be carried. The instability of such a system is found only when an unbalanced downward force exists. The development of controls and films for balloon material proceeded concurrently, but the choice of a non-extensible plastic film was made before the system of control was perfected.

The properties which were given most consideration in the selection of fabric include (1) availability and cost, (2) ease of fabrication and (3) satisfactory chemical and physical properties. Pri-



Figures 3 and 4. Typical rubber balloon arrays.

marily on the cost basis, an extruded film of plastic was found to be superior to fabrics such as silk or nylon with the various coatings.

The physical and chemical properties needed in a balloon material are: (1) chemical stability, (2) low permeability, (3) high tensile strength, (4) low brittle temperature, (5) high tear resistance, (6) high transparency to heat radiation and (7) light weight.

In Table 1 the properies of 7 plastics and 2 coated materials are given. From this data polyethylene and saran appear to be the most suitable films.

Table 1

Fabric	Low Temperature Properties	Permeability	Tensile Strength	Tear Resistance	Ease of Fabrication	Stability to Ultraviolet
Polyethylene	Good	Medium	Low	Good	Good	Good
Saran	Fair	Low	High	Poor	Fair	Fair
Nylon	Good	Low	High	Low	Good	Good
Vinylite	Very poor	Medium	Medium	Good	Good	Good
Teflon	Believed good	Low	High	Good	Cannot be fabricated	Good
Ethocellulose	Good	Very high	Low	Fair	Good	Good
Pliofilm	Poor	High	Poor	Fair	Good	Poor
Nylon or silk fabric coated with:						
Neoprene	Fair	Low	High	Fair	Fair	Fair
Butyl rubber	Good	Low	High	Fair	Fair	Good

Having decided upon the proper fabric to be used, an effort was made to interest a number of companies in the fabrication and production of balloons. The first supplier of balloons made of polyethylene was Harold A. Smith, Inc., Mamaroneck, New York. In these balloons, 4 and 8 mil sheets were heat sealed to form a spherical cell open at the bottom. Load attachment tabs were set into the fabric and loading lines ran from these tabs to a load ring. This method of supporting the load proved to be unsatisfactory.

Subsequently, other companies produced balloons of one type or another for us; the total number and type of balloons purchased is given in Table 2.

Table 2

Plastic Balloons

Company	Film Type, Thickness Diameter, Shape	Special Features	Unit Cost	No. Delivered to Date
Harold A. Smith, Inc.	.004 polyethylene 3-ft.diam., spherical	Prototype	$150.00	4
" " " "	.008 polyethylene 15-ft.diam., spherical	Low permeability	530.00	5
" " " "	.004 polyethylene 15-ft.diam., spherical	Low permeability	530.00	5
General Mills Inc.	.001 polyethylene 7-ft.diam., tear-drop	Stressed tape type seam	20.00	25
" " "	.001 polyethylene 20-ft.diam., tear-drop	Stressed tape type seam	125.00	175
" " "	.001 polyethylene 30-ft.diam., tear-drop	Stressed tape type seam	250.00	15
" " "	.001 polyethylene 70-ft.diam., tear-drop	Stressed tape type seam	900.00	5
The Goodyear Tire & Rubber Company, Inc.	.004 polyethylene 20-ft.diam., egg-plant	Stressed tape type seam and low permeability	475.00	10
Winzen Research, Inc.	.015 polyethylene 20-ft.diam., tear-drop	Low permeability	115.00	20
	Non-Plastic Balloons			
Dewey and Almy Chemical Co.	J-2000 neoprene balloon with nylon shroud of 15-ft. diam., spherical	Internal pressure	325.00	3
Seyfang Laboratories	Neoprene-coated nylon 22.5-ft. diam., spherical	Internal pressure	550.00	10

Teardrop shaped polyethylene balloons were produced by General Mills Inc. and Winzen Research, Inc., both of Minneapolis, Minnesota. The General Mills cells were supplied in four sizes with the diameters of 7, 20, 30 and 70 feet to carry loads to varying altitudes. A 20-foot balloon is shown in Figure 5.

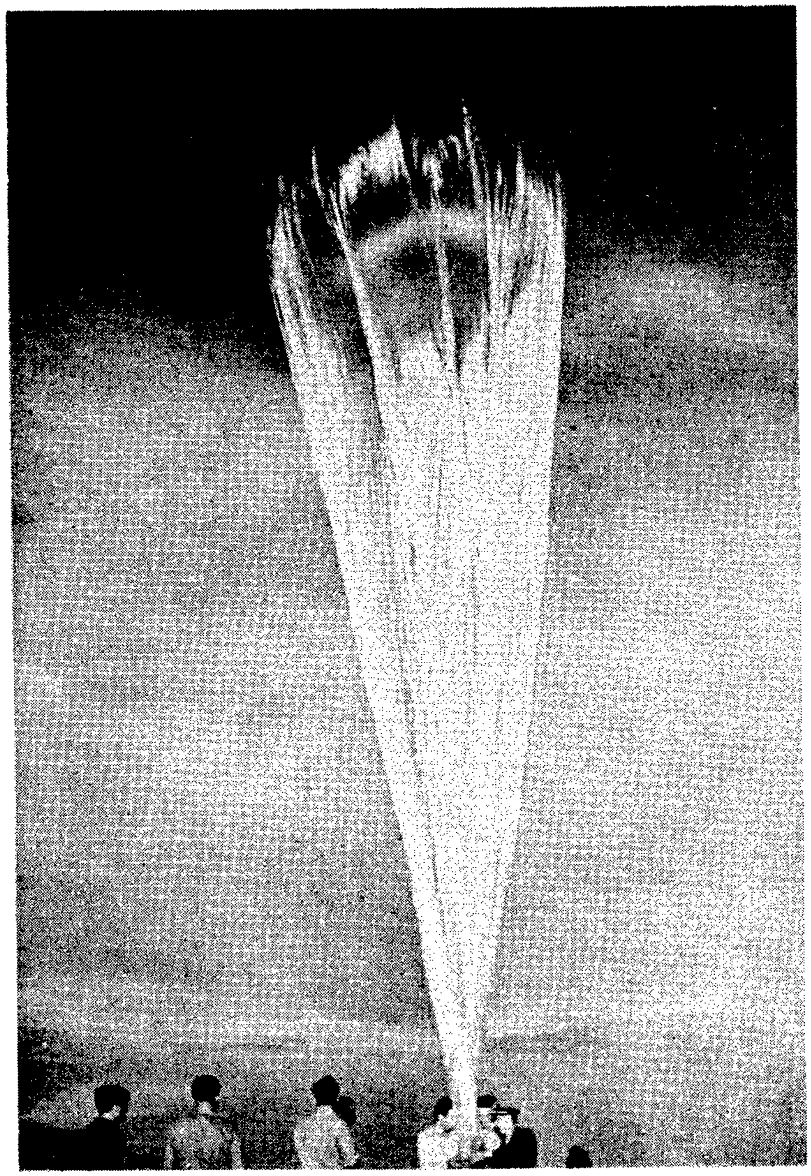


Figure 5. 20'-Diameter, teardrop polyethylene balloon.

In all of these, film is .001" polyethylene, butt welded with fiber tape laid along the seams to reinforce the seal, and to carry and distribute the load. These tapes, which converge to the load ring at the bottom, actually support the load (Figure 6). An open bottom permits the escape of excess lifting gas and thus prevents rupture.

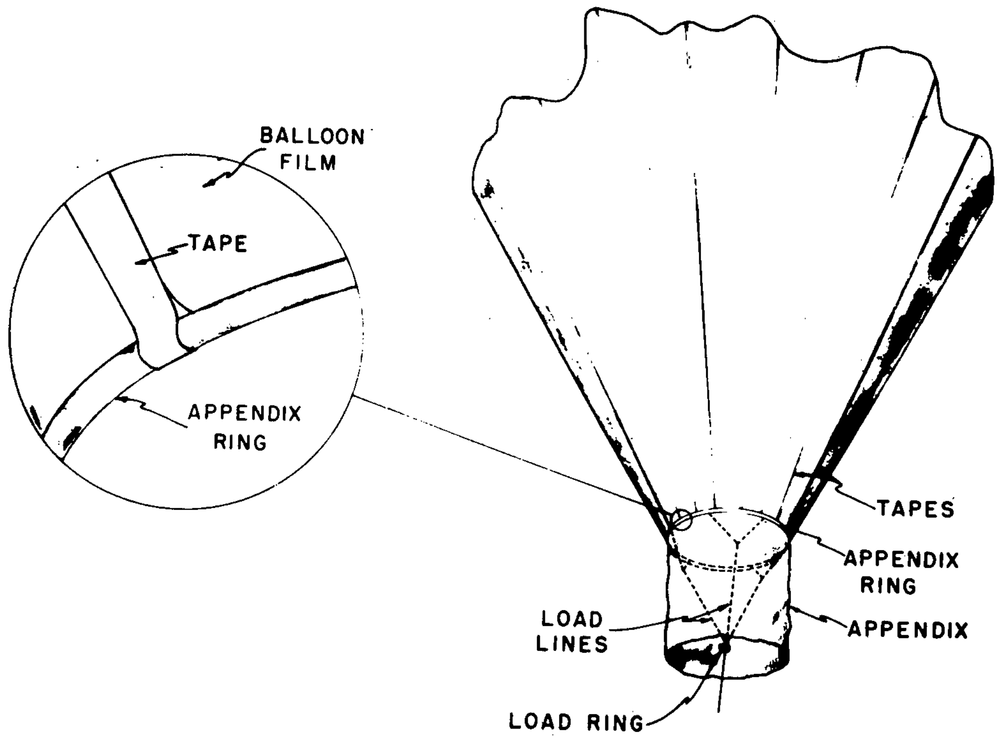


Figure 6. Appendix detail, polyethylene balloon.

On the Winzen balloons, which are made from .015" polyethylene, all but two of the balloons were made with similar fiber tape reinforcements; these two were produced without tapes and both of them have been flown with no evidences of unsatisfactory performance.

The eggplant shaped balloon produced by The Goodyear Tire & Rubber Company, Inc. has been flown with satisfaction, but the exact amount of diffusion, which is expected to be low from this balloon, is not yet known.

C. Internal-Pressure Balloons

From a theoretical standpoint the most satisfactory means of keeping a balloon at constant pressure-altitude is to use a non-extensible cell with very low diffusion through the walls and one capable of maintaining super-pressure in excess of that lost with reductions of gas temperature. Such a balloon could be sealed off completely or a pressure-activated valve could be used to permit efflux of the gas when the bursting pressure is approached. The neoprene-coated nylon balloon built by Seyfang Laboratories (Figure 7) has been used with a valve set to prevent rupturing.

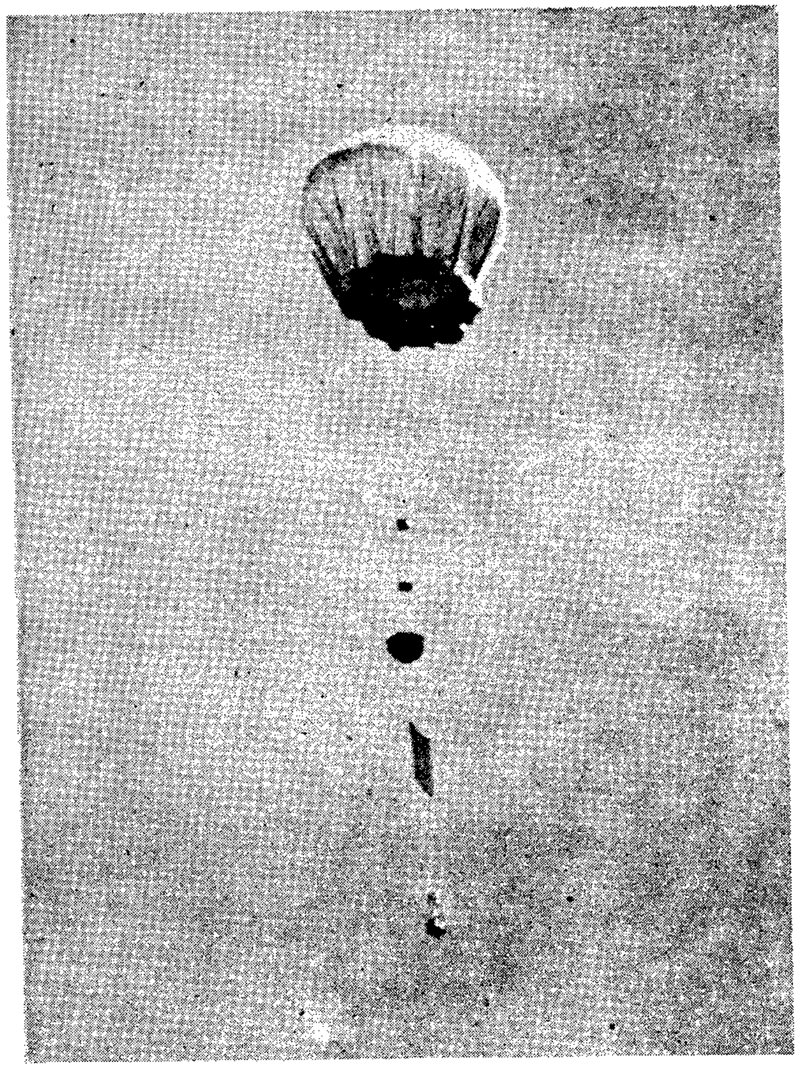


Figure 7. Neoprene-coated nylon balloon, two-thirds inflated.

The fabric has been coated with a metallic paint to minimize the effects of radiation. However, the values of superheat obtained by the gas when the balloon is in the sun have been of the order of 30°C. The amount of buoyancy lost when circulation or sunset cuts off the superheat is so large that it is not possible to carry enough ballast to sustain the system under these conditions. On the other hand, the loss of buoyancy through a sealed-off Seyfang balloon at 4100 feet MSL is of the order of 50 grams per hour which is significantly less than the loss expected from a 20-foot, 1 mil polyethylene cell in flight conditions. (With the appendix aperture sealed, such a cell shows a loss of lift of about 40 grams per hour when one-fifth inflated at sea level).

One other type of balloon which has been used as a super-pressure balloon is the neoprene J2000 balloon of Dewey and Almy, surrounded by nylon cloth shroud. The rubber balloon normally would expand until it reached bursting diameter, but when enshrouded, it is limited to the volume of the shroud. The difficulties in launching and flying this balloon are not unusually great, but on each of the several tests which have been made to date improper handling has been a possible cause of the early rupture of the balloon. It is believed, however, that such a balloon is not especially suitable for long flights because of the deterioration which occurs in the neoprene in the presence of sunlight. Perhaps a shroud of material which would filter out the ultraviolet rays would protect and lengthen the life of such a balloon.

Despite the success of the Japanese silk or rice-paper balloons, which were constructed on a super-pressure principle, it is not believed practical at this time to develop a balloon of such strength that it would successfully withstand and retain pressure increases corresponding to the temperature changes from night to day as the superheat of absorbed sunlight is gained. The super-pressure with a neoprene-coated nylon balloon, for example, would be approximately 0.5 psi. That such a balloon could be built is unquestioned. The cost of production, however, appears at this time to be unwarranted.

D. Altitude Controls

Beginning with the arrays of rubber balloons which were first used, various systems of dropping ballast, both solid and liquid, have been attempted with the aim of exactly compensating for the loss of buoyancy which is occasioned as the lifting gas diffuses or leaks through the balloon. On the early rubber balloons only rough incremental ballast dropping was employed. At that time it was decided not to use sand as ballast since most sand contains some water which may freeze while aloft. Further, it is easier to control the flow of a liquid ballast than it is to control sand particles. In the investigations for a suitable liquid ballast the petroleum product known commercially as Mobil Aero compass fluid was finally settled upon. These investigations included tests of cloud point, freezing point, and also density and viscosity over a large range of temperatures. The compass fluid is especially suitable for ballast work in high altitudes, since it freezes below -80°C and will flow readily at low temperatures. Also, this fluid will absorb only a very slight amount of water which might freeze aloft.

Basically three different principles have been used in the control of ballast flow. The first of these is calculated constant flow; the second is displacement-switch control; and the third is rate-of-ascent switch control.

(1) Constant Flow

In the simplest of the control systems, liquid ballast is allowed to flow continuously through an orifice (Figure 8) at a predetermined rate. This rate is set to slightly exceed the ex-

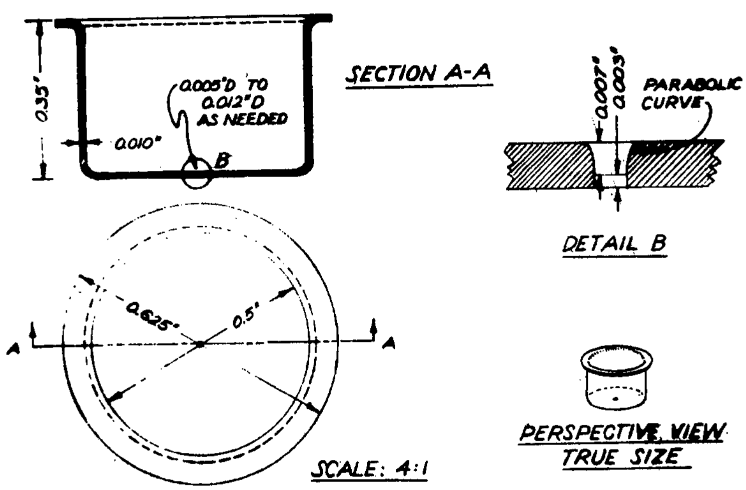


Figure 8. Orifice for fixed-rate ballast flow.

pected loss of lift of the balloon due to leakage and diffusion. If this method is successfully used, the balloon stays full because the gas remaining in it has less load to support. Therefore, the balloon will rise slowly as ballast is dropped, maintaining equilibrium between the buoyancy and the load. In the General Mills 20-foot balloon, for example, diffusion losses are about 200 grams per hour at altitudes near 40,000 feet. The balloon at its ceiling of 40,000 feet with a 26-kilogram payload rises about 700 feet with each kilogram of ballast dropped. This means that such a balloon using this constant-flow type control will float at a "ceiling" which rises at the rate of about 140 feet per hour. Constant flow was first obtained by use of the manual ballast valve shown in Figure 9. Due to excessive clogging of this valve, caused by its annular ring opening, gate-type valves were tested, and finally the use of simple orifices of various sizes replaced the manual ballast valve.

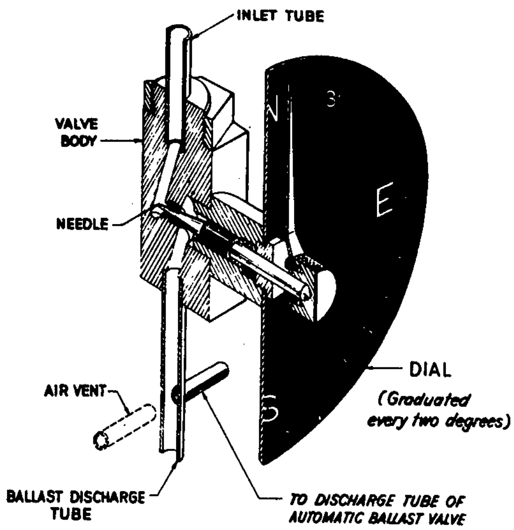


Figure 9. Manual ballast valve.

(2) Displacement Switch

The displacement principle in ballast control has been used in two different types of valves. The first of these, called the "automatic ballast valve," used a needle valve, controlling ballast flow by an aneroid capsule to which the needle was attached (Figure 10). The aneroid capsule was open to the atmosphere on ascent; as the balloon began to descend to a region of higher pressure, a minimum pressure switch was used to seal off the capsule and further descent caused ballast flow. (For details see Technical Report No. 1, Constant Level Balloon Project, Research Division, College of Engineering, New York University, New York, N.Y., 1948.)

There are three undesirable features of this system. Greatest is the effect of temperature changes on the air sealed in the capsule. Seal-off pressure acts as a datum plane. Any increase from this pressure causes compression of the aneroid, and ballast flows proportionally to the difference from seal-off pressure. However, with changes of temperature of the entrapped air, the activation pressure of the valve changes, the floating level is thus also a function of temperature of the gas in the aneroid.

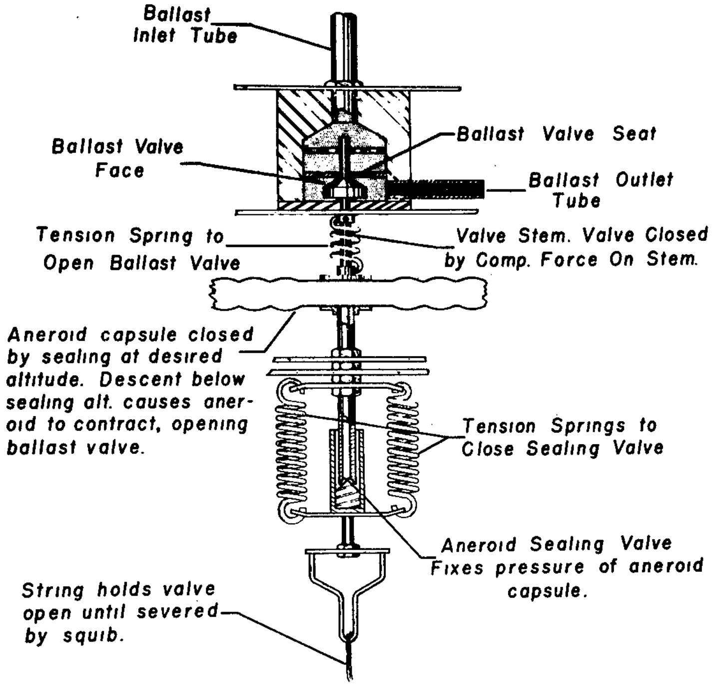


Figure 10. Automatic ballast valve.

The second undesirable feature of the automatic ballast valve system is the lag induced by the use of a minimum pressure switch to seal off the aneroid capsule. This is in addition to the lag of the aneroid itself. If a mercury switch is used, the differential between minimum and seal-off pressure is about 8 millibars; with a less dense liquid, the operation will still require about a 2-millibar difference. If the sealing is done by a fixed pressure switch, it is then necessary to predict the altitude to which the balloon will rise. Failure to reach this height would leave the aneroid open and useless. Deliberate under-estimation of the ceiling causes a relatively long period of uncontrolled slow descent before control begins.

The third unwanted feature is the waste of ballast which flows during both descent and ascent of a balloon whenever it is below the seal-off elevation. Since the balloon is no longer "heavy" when its downward motion has been arrested, flow during the return to the datum plane is needless and indeed will cause an overshoot, hence the unnecessary exhaust of some lifting gas.

The effects of temperature on the aneroid capsule of the automatic ballast valving system were eliminated by the use of a ballast switch which uses a vacuum-sealed aneroid, set to permit ballast flow through a valve whenever the balloon is below a given pressure altitude. In this system the minimum pressure switch and the lag caused by its use are eliminated. This displacement-switch control has the disadvantage that the flow which it permits is not proportional to the displacement of the balloon below a datum plane but is constant through the valve. Normally this flow is large to permit rapid restoration of equilibrium. A second disadvantage is the requirement of batteries to supply power to the electrically operated valve. However, the advantage of eliminating the temperature effects on the aneroid compensate for these two comparatively minor disadvantages.

In practice, the displacement switch has consisted of a modified radiosonde modulator in which the standard commutator is replaced by a special bar which is an insulator above a certain point and a conductor at lower levels (higher pressures). When the aneroid pen arm is on the conducting section of the commutator, a relay opens the ballast valve. To prevent excessive flow on ascent, the pen arm rides on an insulated shelf above most of the contact segment of the commutator (Figure 11).

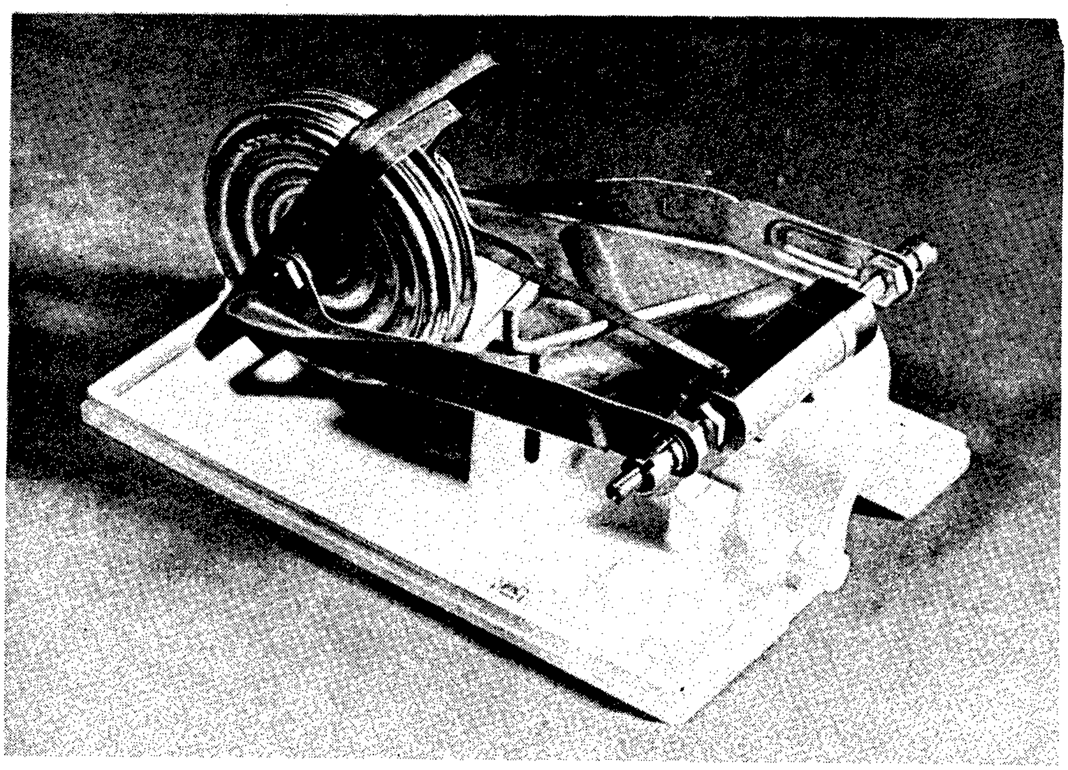


Figure 11. Pressure displacement switch.

The pen drops off the shelf at a safe distance below the expected pressure altitude and ballast then flows until the pressure pen reaches the insulating section of the commutator. In order to prevent the overshoot mentioned as one undesirable feature of the automatic ballast system, the high pressure end of the insulator may correspond to the expected maximum altitude of the balloon, any loss of lift due to impurities or escape of lifting gas will cause the balloon to level off at a ceiling within the ballast-dropping range. Continued ballast dropping will result in the rise of the balloon. Thus, an overestimation of the ceiling is not as critical as in the case of the previous system.

(3) Rate-of-Ascent Switch

With the displacement-switch control just described there remain the problems of ballast waste and balloon oscillation resulting from discharge of ballast during rises of the balloon after a descent has been checked. To eliminate this, a ballast-control switch acting on the rate of rise of the balloon is put in series with the displacement switch to close the ballast flow circuit only when the balloon is coming down or floating below pressure altitude. When it is rising, no ballast flow is permitted. This "rate-switch" is seen in Figure 12.

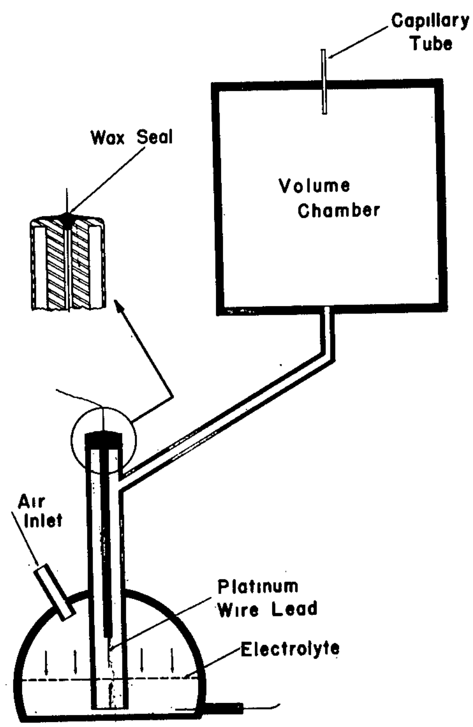


Figure 12. Rate-of-ascent switch.

A glass flask is open to atmospheric pressure through a fine capillary tube. With various rates of change of pressure, various differential pressures exist between the air in the flask and the outside air. This pressure difference controls the level of liquid in a manometer switch, filled with 24% hydrochloric acid. When the internal pressure is 0.2 mb more than the ambient pressure, the switch opens and ballast flow is stopped even though the balloon may be below the floating level. (The switch is set so that a rate of change of .1 mb/minute acting for three or more minutes will open the switch.) By thus restricting flow when the balloon is rising, balloon oscillations are minimized and ballast is conserved. A sketch of this operation is shown as Figure 13.

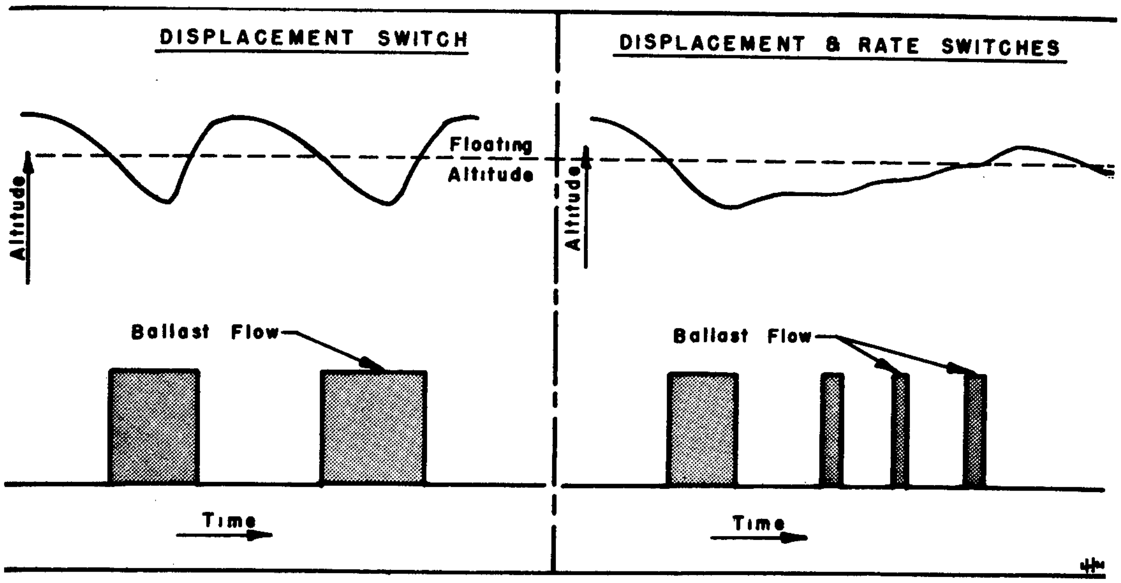
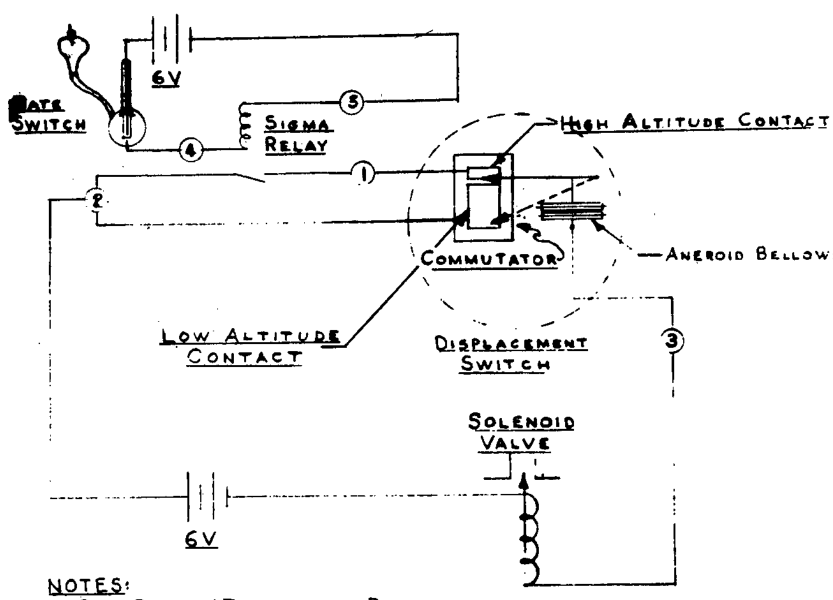


Figure 13. Height-time curve, showing ballast control action.

Since the rate switch is much more delicate than the displacement switch, safety considerations have caused the combined control to be supplemented by a pure displacement switch control. In this, the conducting segment of the pressure modulator is divided, and only a limited pressure height range (set for desired floating level) is controlled by both switches in series. If the rate switch is damaged at launching (by spilling some of its electrolyte, for instance) or in flight (perhaps by evaporation of the electrolyte) and the balloon descends, simple displacement control becomes effect when the high pressure (lower altitude) segment of the conductor is touched by the pressure pen. The switch circuit is seen in Figure 14.



NOTES:
BATT. PACK IN TRANSMITTER BOX
SIGMA SENSITIVE TYPE 5F RELAY- COIL
RESISTANCE-16000 OHMS
DISPLACEMENT SWITCH- ED48-107
RATE SWITCH- ED48-115
SOLENOID VALVE- ED48-110
USE 4FH-6 V LITHIUM CHLORIDE BATTERIES (BURGESS)
FOR DETAILS OF DISPLACEMENT SW. SEE ED48-126

Figure 14. Circuit for ballast control with combined displacement and rate-of-ascent switches.

Figure 15 is a theoretical height-time curve, showing when ballast would be dropped using such a control and the resulting balloon behavior. During ascent the pressure pen is kept off the commutator bar until Point 1 where it falls onto the low-altitude conducting segment. (The shelf has been set so that the pen will fall onto the low-altitude segment in order that a ballast signal will be received for a short period of time, indicating that the system is working properly. The balloon rises and ballast flows until the pressure pen reaches Point 2, the beginning of the region where both switches in series control the ballast. As long as the balloon continues to rise, no flow occurs. Should the maximum altitude be above the control level , no ballast will flow until the balloon descends to that point. Then, with both controls operating, ballast will flow only on the descending and floating portions of the flight below control level. A second course is illustrated, wherein the rate-switch has failed. There the balloon descends to Point 2 and oscillates about this level, as a result of displacement switch actions alone.

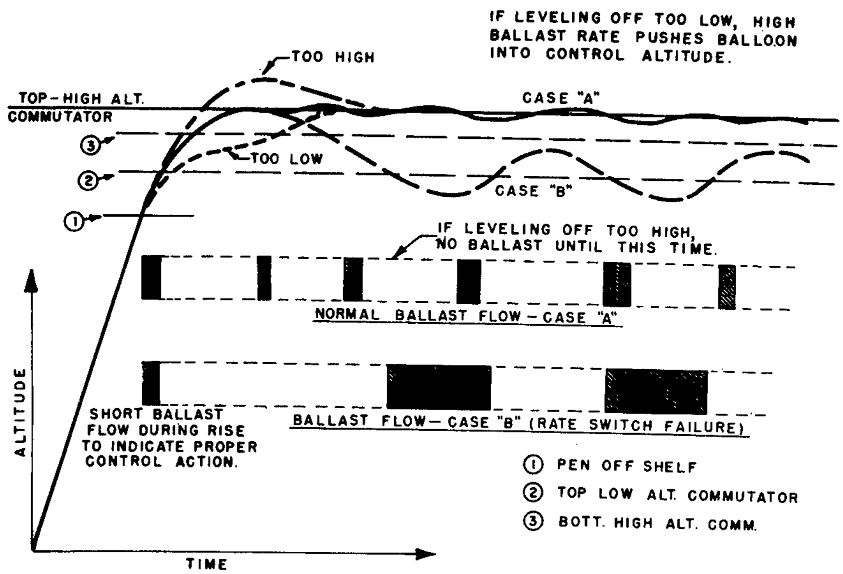


Figure 15. Theoretical height-time curve.

(4) Rate-of-Descent Switch

It may at times be desirable to control a balloon merely by a switch activated at any given rate of descent. This could be accomplished merely by "reversing" the rate-of-ascent switch. This type of control would prove to be quite difficult, however, for a constant level flight. One flight, No. 97, was made using a type of rate-of-descent switch as shown in Figure 16. In

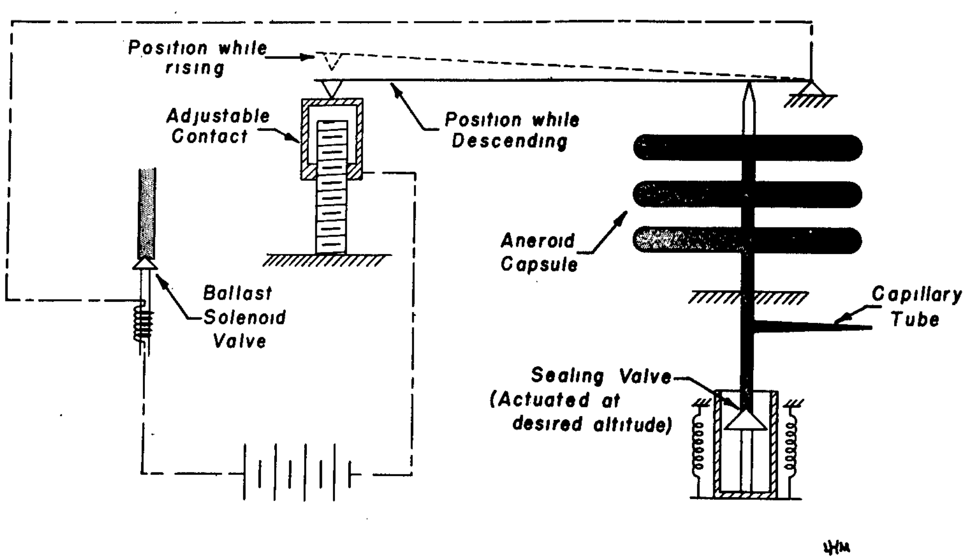


Figure 16. Rate-of-descent switch.

this switch a circuit is closed when the rate of descent exceeds 1/5 mb/minute, allowing ballast to flow. The record of Flight 97 indicates that good control was obtained for a four-hour period using this switch. However, the instrument is so delicate and susceptible to temperature effects that its use is not advised.

E. Flight Simulation

To make laboratory tests on the control equipment just described, a flight-simulation chamber has been built combining a bell jar and a temperature chamber. A drawing of the temperature chamber designed and built at New York University is shown in Figure 17. (Investi-

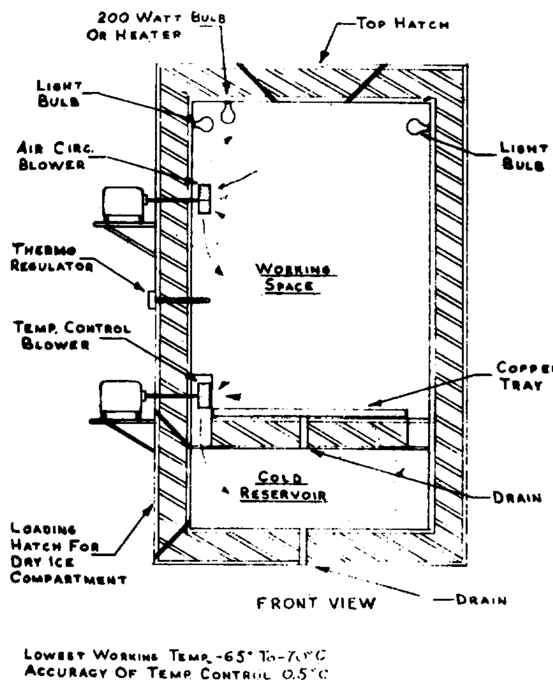


Figure 17. Temperature control chamber.

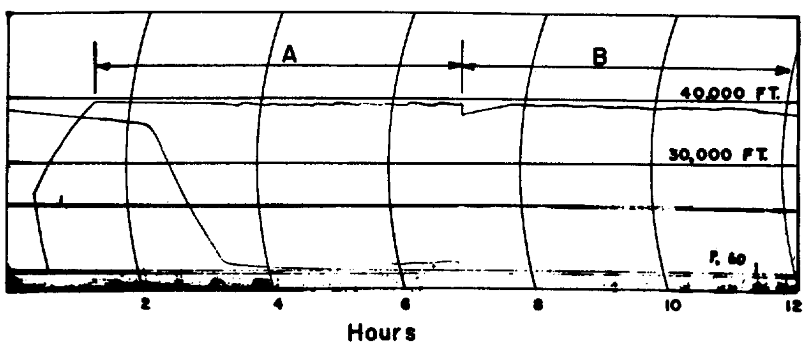
gation of commercially sold chambers showed that the cost of purchasing a temperature chamber of the size desired would be prohibitive.) First designs called for the use of a freon refrigerating system; however, use of dry ice as a coolant proved to be more advantageous. This chamber, with its automatic control, can hold temperatures as high as +100°F and as low as -90°F within 5° for a period of several hours. Dry ice consumption at -60°F is approximately 150 pounds for a 24-hour period.

It is possible, using a bell jar for flight-similitude studies, to arrange switches so that the vacuum pump is turned off and on at the same time that ballast is normally required in flight. This system simulates the effect of rising and falling in the atmosphere and indicates the effectiveness of the controls which have been applied.

In order to simulate flight, it is necessary that three conditions be maintained within the system. The first is that a leak of air into the bell jar is permitted at a rate of pressure increase which has been observed during balloon descent. A large lag chamber is connected into the bell jar to supply the second condition which is a delay similar to that inherent in the control action on an actual balloon flight. It is necessary to properly adjust the volume of such a lag chamber to obtain the desired magnitude of control action.

A third requirement is that the response of the vacuum pump must correspond to that response which has been observed when a balloon system drops ballast. In order to measure this, the control mechanism has been allowed not only to switch the vacuum pump on and off but also to actuate the standard ballast-flow equipment. This system may be adjusted so that the amount of pressure change which a single period of pumping produces accurately represents the amount of ballast thrown off during flight.

The barogram shown in Figure 18 is an example of such a test. On this test the rate-of-ascent ballast switch was added to the displace-



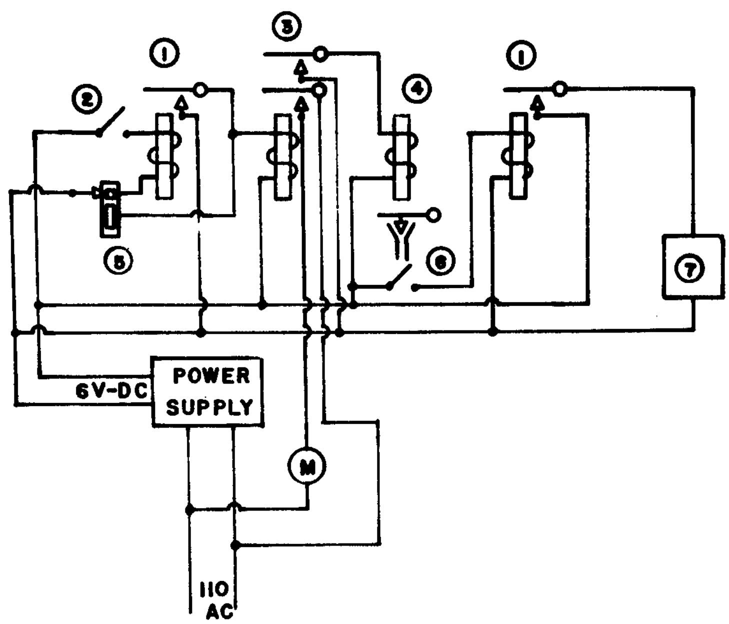
Flight Similitude Record Of Pressure

A- Displacement Switch Operating.
B- Displ. & Rate Of Ascent Switches Operating.

Figure 18. Sample barograph record.

ment switch after the latter had operated for a period of six hours. The combination of the two is seen to have effected a reduction in the amplitude and frequency of oscillations induced by the servo system. In fact, under the influence of both controls, oscillation is almost undetectable.

As a consequence of such tests, it is possible to predict the type, size and frequency of oscillations which the servo-control equipment will introduce into the balloon flight. This is especially significant since it is known from flights on which no control equipment was included that oscillations do occur naturally within the atmosphere, apparently as a result of vertical cellular convection currents. By knowledge of the frequency of oscillation caused by a given control system it is possible to analyze oscillations and determine which are caused by control and which are atmospheric. The wiring diagram of the flight-similitude system is shown in Figure 19.



NOTES

(1) Sigma Relay Type 5F
(2) Rate Switch - ED 48-115
(3) Heavy Duty Relay, Guardian Series 200dpst
(4) Ballast Solenoid Valve - ED 49-2
(5) Displacement Switch - ED 48-107
(6) Auto Syphon
(7) Counter
(M) Pump Motor

Figure 19. Wiring diagram, flight-similitude system.

The vacuum system is shown in Figure 20.

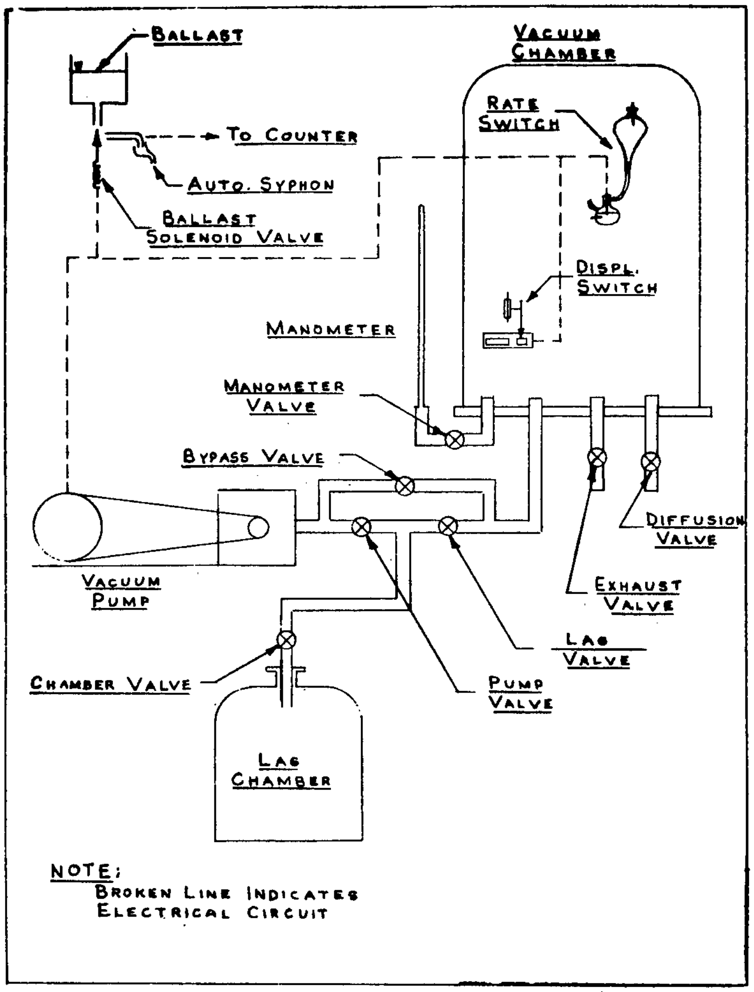


Figure 20. Physical layout, flight-similitude system.

This equipment has been used in testing instruments to be flown and also equipment which is used in the launching and preparation before release. For example, the Du Pont S64 squibs, which have been used in conjunction with the flight-termination switches and also for severing launching lines, were tested in this chamber and found to fail when subjected simultaneously to cold temperature (-50°C) and low pressures (10 millibars) although tests at either low temperature or low pressures alone produced no failures. As a result of these tests, a new squib, the S59, has been produced by Du Pont and is used in current flights. Other equipment which has been tested in the bell jar and the cold chamber includes the Lange barographs and the Olland-cycle pressure-measuring instruments.

F. Flight Termination Gear

The rate of descent when controlled balloons are falling after exhausting all ballast is sometimes as slow as 50 feet per minute. This means that several hours might be required to fall through the lanes of aircraft traffic, increasing considerably the hazard to aircraft (admittedly very small). To minimize this possibility, units have been added to the flight train to cause a rapid descent after the balloon system has descended to some critical value, say 20,000 feet. One such destruction system, using a flight-termination switch, is shown in Figure 21. It consists of a pressure-activated switch, triggered on descent only, an explosive charge used to sever

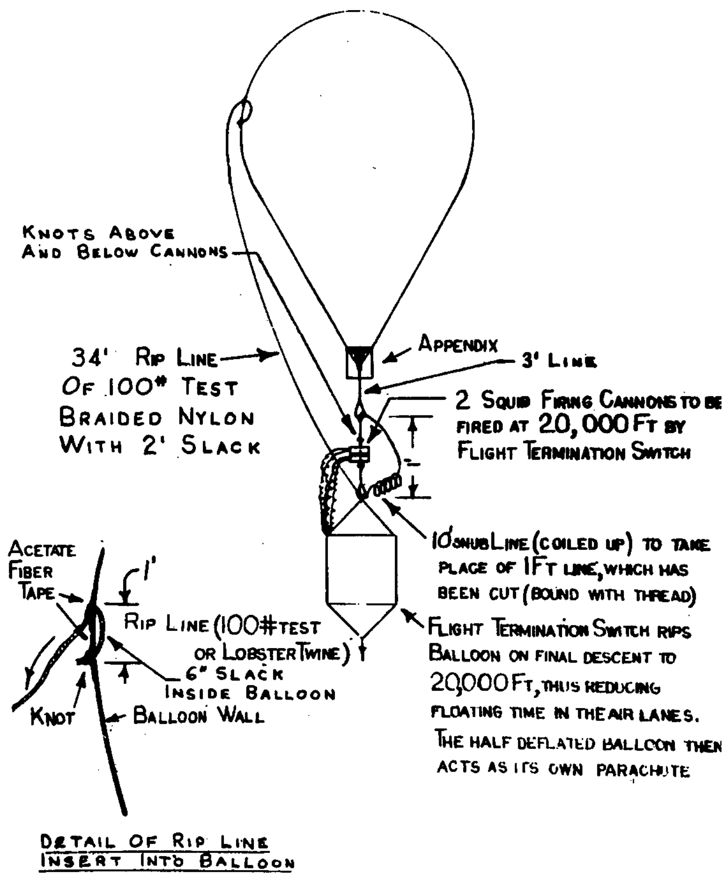


Figure 21. Flight termination equipment.

the main load line, a rip line attached to the balloon near the equator and a snub line which takes up the strain after the load has fallen a few feet.

When the contact is made, the load line is cut and the entire weight of the dependent equipment is used to pull out a section of the balloon wall. Through this rupture, the lifting gas can escape, and the balloon descends, using the upper portion as a parachute. The rate of descent has been observed to vary from 600 to 1500 feet per minute when this system is employed.

For some special applications it has been desirable to cause the balloon to descend after some predetermined time, instead of waiting for the descent to air traffic lanes. In these cases, a clockwork switch has been used instead of the pressure-activation unit. When clocks are used they are kept free of lubricants which will freeze. The best results have been obtained from the use of a Dow Corning Silicone (DC 701) diluted with 30% kerosene. If this is not available, it is better to send up a clock without any lubrication. Given relatively loose mechanism (a cheap alarm clock) the differential expansion of parts which is encountered at low temperatures is apt to cause less trouble than does the congealing of standard lubricants.

IV. EQUATIONS AND THEORETICAL CONSIDERATIONS

Development of a controlled altitude balloon has led to investigation of many theoretical considerations applicable both directly and indirectly to the description of variables encountered in balloon control. Some of these relationships have been derived directly from standard hydrodynamic or thermodynamic principles; others come from an empirical study of results of laboratory tests and actual balloon flights. In this section we will investigate these theoretical considerations and endeavor to correlate them with actual flight results. A more simple investigation of the equations necessary for the launching and tracking of a controlled altitude balloon is contained in Part II of this report, "Operations."

We shall first consider the relationships which aid in evaluating the elementary characteristics of non-extensible balloon flight and those which are helpful in carrying out inflation and launching operations of such balloons. Next, we shall discuss more complex considerations involved in balloon flights.

A. Floating Altitude and Altitude Sensitivity

To determine the altitude at which a non-extensible balloon will float we must consider the weight of the balloon system, the volume of the balloon, and the densities of the lifting gas and the air. [If the lifting gas is 98% helium (molecular weight 4.50 lb./lb. mol), the lift of a unit of gas will be 24.4 lb./lb. mol. Similarly, if 98% hydrogen were the lifting gas, the lift would be 26.6 lb./lb. mol.] By using these three basic parameters, we can obtain an expression for the molar volume at which the balloon will float:

$$(1) \quad MV = \frac{\text{Balloon Volume x Gas Lift}}{\text{Gross Load}}$$

[It may be noted from this equation that a balloon can float at molar volumes less than that computed for maximum balloon volume (i.e., when it is not full). However, under these conditions the balloon would be in neutral equilibrium, since any vertical force would cause it to rise or fall until a force in the opposite direction stopped it. This is also the case with floating extensible balloons.]

To convert from molar volume to equivalent altitude we must know the pressure-temperature distribution of the atmosphere in which the balloon will float. Since it is difficult to obtain an accurate distribution for each flight, the atmospheric model as drawn up by NACA standards has been used. In general the error obtained in using the NACA standard is not great, but if greater refinement is desired, data obtained from averaged radiosonde observations over a given launching site can be used.

From such knowledge of the distribution of pressure and temperature, we may plot a curve of molar volume vs. altitude by use of the following equation:

$$(2) \qquad MV_z = 359 \frac{ft^3}{lb\ mol} \times \frac{T_z}{273^\circ K} \times \frac{1013.3\ mb}{p_z} \quad \frac{ft^3}{lb\ mol}$$

By use of such a plot we easily find the floating altitude of a full non-extensible balloon by use of equation (1) to find molar volume, and then of the plot of equation (2) to find altitude.

The two equations have been combined and graphed in the form of an altitude vs. gross load chart with helium as the lifting gas for various balloon sizes and various release sites in the "Operations" section of this technical report (Part II, page 108).

For the NACA standard atmosphere we may derive an equation for altitude sensitivity by use of the molar volume-altitude relationship. This is most easily done by plotting molar volume vs. altitude on semi-logarithmic paper, since the curve of molar volume vs. altitude from 40,000 to 105,000 feet (where a constant lapse rate of zero is assumed) is approximately a straight line on semi-log paper. The general form of the equation for this portion of the atmosphere is $y = ae^{bz}$ where y is the molar volume and z the altitude.

It is possible to determine empirically the constants a and b. For example, using the molar volume at 50,000 feet, we find from

*359 ft^3 = Molar volume of air at standard conditions (273°K, 1 atm. pressure) the equation 2500 $ft.^3/lb.$ mol = ae^{50b} where 50 is the expression for altitude in thousands of feet. Similarly, at 70,000 feet, 6450 = ae^{70b}, and by solving to eliminate a, we find 2.58 = e^{20b} or 20b = .95, and the constant b is equal to .0475. Thus, the equation may be written:

$$(3) \qquad y = ae^{.0475z}$$

y was originally defined as the molar volume, equal (for 98% helium) to:

$$\frac{\text{Balloon Volume} \times 24.4}{\text{Gross Load}} = \frac{K}{W}$$

In turn, $\frac{K}{W} = ae^{.0475z}$, where z is the expression for altitude in thousands of feet. From this relationship, we may solve for W, the gross load.

$$(4) \qquad W = \frac{K}{a} e^{-.0475z}$$

$$(5) \qquad \ln\left(\frac{Wa}{K}\right) = -.0475z$$

or:

$$(6) \qquad \ln W + \ln\frac{a}{K} = -.0475z$$

Differentiating with respect to W:

$$(7) \qquad \frac{dz}{dW} = -\frac{21.052}{W} \frac{ft}{lb}$$ where W is gross load in lb.

We see that the value of the constant a is unimportant here, and the expression is independent of balloon volume, as long as it does not vary with time. Included is the assumption that over a short period of time buoyancy of lifting gas does not change.

Thus, we have an expression for A, the altitude sensitivity, which is valid between 40,000 and 105,000 feet. Similarly, it is possible to evaluate altitude sensitivity for operation between 0 and 30,000 feet. A in this range is equal to $\frac{31,400}{W}$ ft./lb.

A plot of altitude sensitivity against load is shown on page 109 of the "Operations" section (Part II of this technical report).

We may use this equation to approximate the rise of a full balloon system when controlled by overcompensated constant ballast flow:

$$(8) \qquad \frac{dz}{dt} = \frac{dW}{dt} \times A$$

where z is the balloon ceiling, t is time, and W is total weight of the balloon system.

B. Rate of Rise

The equation of Clarke and Korff:

$$(1) \qquad \frac{dz}{dt} = 272 \frac{F^{1/2}}{G^{1/3}} \frac{cm}{sec}$$

has been used to obtain the relationship between rate of rise and free lift (or excess buoyancy) for a balloon system of any given weight. For practical use, the equation has been modified to:

$$(2) \qquad \frac{dz}{dt} = 1486 \frac{F^{1/2}}{G^{1/3}}$$

where F is free lift in pounds and G is gross lift in pounds.

Although this equation was derived for use with extensible spherical balloons, it predicts closely the performance of non-extensible balloons while they are rising to floating level. An average value for the constant in equation (2) from actual flights is 1600 ft./min(lb.)$^{1/6}$

The deviation from this relationship, evidenced in several flights, may be due to several variations from the assumptions upon which the equation is based. This deviation has in general been an increase of rate of rise of from 0 to 25% at higher altitudes.

To explain this increase, let us first investigate the changes which may occur in the free lift. If any gas leaves the balloon because of leakage through the balloon or the appendix, the free lift will be reduced and the rate of rise will decrease (as it does after the balloon is full and "levels off"). Therefore, this variation may be ruled out when considering rise before the balloon becomes full.

Free lift will vary with changes of temperature of the lifting gas with respect to the free-air temperature. A change of this sort can be caused by acquisition of superheat of the lifting gas, or by temperature decrease or increase caused by adiabatic expansion or compression of the lifting gas. (These items will be discussed later in this report.) Actual temperature measurements during rising portions of flights indicate that there is no appreciable temperature difference between the lifting gas and free air. Evidently the effect of ventilation as the balloon moves through the air causes the lifting gas to remain at a temperature approximating that of the air, and the increase of lift due to temperature variation is small in magnitude.

Since changes in the value of free lift appear incapable of causing any appreciable increase in rate of rise, other possible variations such as a change of the drag, or fluid friction, effect must be considered.

The equation of Korff is based upon the assumption that the effect of the change in Reynolds number and the change in size are of equal magnitude, but in opposite directions. Therefore, these variables are eliminated to obtain the simple engineering formula of Korff. With a non-extensible balloon, however, the change of drag effect is probably less than the effect of change of Reynolds number. Therefore, it is likely that the rate of rise would increase with altitude. The change in drag effect may be realized by a decrease of relative size of the flabby, unfilled portion of the balloon. Thus there will be a decrease of the drag caused by flow of air past this flabby portion as the shape of the balloon changes; the result will be an increase in the rate of rise of the system.

C. Superheat and Its Effects

The effect of the heating of lifting gas by the sun's rays has long been of interest to those using balloons for atmospheric investigation. In cosmic-ray studies using freely extensible balloons, this heating effect was used to advantage in extending the length of flights. These flights were often released at night using the heat added at sunrise to replenish lift lost during the night by diffusion and leakage.

In constant-level balloon work, using non-extensible balloons, the effect of superheat of the lifting gas is more often a disadvantage than an advantage. The disturbance of the flight is not great when the gas acquires this superheat but may be disastrous when the superheat is lost. It is at this time that a large amount of ballast is required to keep the balloon system afloat.

Let us investigate the effects of gain and loss of superheat on a full, non-extensible balloon. We shall try to explain these effects in terms of percentage loss or gain of lift of the balloon system by use of simplified engineering formulas. First, the general formulas:

(1) Lift: $L = V_b(d_a - d_g)$, where

$V_b =$ balloon volume

$d_a, d_g =$ density of air and lifting gas, respectively

(2) Density: $$d = \frac{p}{RT}$$

p, R, T = pressure, specific gas constant, and temperature of the air or lifting gas

(3) Let: $$B = \frac{R_a}{R_g} \quad \left(= \frac{M_g}{M_a} \right)$$

At any two positions:

$$L_1 = V_1 (d_{a_1} - d_{g_1})$$

$$L_2 = V (d_{a_2} - d_{g_2})$$

Investigating the gain of superheat, since there is no change of volume $V_1 = V_2$ and:

(4) $$\Delta L = L_2 - L_1 = V_1 (d_{a_2} - d_{a_1} - d_{g_2} + d_{g_1})$$

Assume now that the balloon carries no internal pressure and that the difference in lift does not cause the balloon system to pass through any appreciable atmospheric pressure difference (in the case where the balloon is floating at 40,000 ft. MSL a change of 1000 ft. would be only 9 mb, or a 5% change).

Therefore:

$$p_{a_1} = p_{a_2} = p_{g_1} = p_{g_2} = p$$

Assume also that initially the air and lifting gas are at the same temperature and that the air passes through no appreciable temperature change. Then:

$$T_{a_1} = T_{a_2} = T_{g_1} = T_1$$

Then, making use of our two assumptions and substituting equation (2) into equation (4), we have:

$$\Delta L = Vp \left(\frac{1}{R_a T_1} - \frac{1}{R_a T_1} - \frac{1}{R_g T_{g_2}} - \frac{1}{R_g T_1} \right)$$

$$= \frac{Vp}{R_g} \left(\frac{1}{T_1} - \frac{1}{T_{g_2}} \right)$$

and:

$$\frac{\Delta L}{L_1} = \frac{\frac{1}{R_g}\left(\frac{1}{T_1} - \frac{1}{T_{g_2}}\right)}{\frac{1}{T_1}\left(\frac{1}{R_a} - \frac{1}{R_g}\right)}$$

(5) $$\frac{\Delta L}{L_1} = \frac{B}{1-B}\left(\frac{T_{g_2}-T_1}{T_{g_2}}\right)$$

or, for small temperature differences, we have:

(6) $$\frac{\Delta L}{L} = \frac{B}{1-B}\left(\frac{\Delta T}{T}\right)$$

With increasing temperatures, there will be an unbalance in the direction of greater altitude. While climbing to a greater altitude the balloon will valve gas and come to equilibrium at a new level. Thus the effect of gain of superheat with a full non-extensible balloon will be a slight increase of altitude.

Investigating the case where an initial amount of superheat is lost:

(7) $$\Delta L = V_2(d_{a_2} - d_{g_2}) - V_1(d_{a_1} - d_{g_1})$$

and since the balloon volume will decrease with cooling of the lifting gas:

$$V_2 = V_1 \frac{T_{g_2}}{T_{g_1}} \qquad \text{(assuming constant } p\text{)}$$

Therefore, again making use of the assumptions that:

$$p_{a_1} = p_{a_2} = p_{g_1} = p_{g_2} = p$$

and:

$$T_{g_2} = T_{a_1} = T_{a_2} = T_2$$

Combining equation (2) and equation (7), we have:

$$\Delta L = V_1\left[\frac{T_2}{T_{g_1}}\left(\frac{p}{R_a T_2} - \frac{p}{R_g T_2}\right) - \left(\frac{p}{R_a T_2} - \frac{p}{R_g T_g}\right)\right]$$

$$= V_1\left(\frac{p}{R_a T_{g_1}} - \frac{p}{R_g T_{g_1}} - \frac{p}{R_a T_2} + \frac{p}{R_g T_{g_1}}\right)$$

(8) $$= \frac{pV_1}{R_a}\left(\frac{1}{T_{g_1}} - \frac{1}{T_2}\right)$$

Then:

$$\frac{\Delta L}{L_2} = \frac{\frac{1}{R_a}\left(\frac{1}{T_{g_1}} - \frac{1}{T_2}\right)}{\frac{1}{T_2}\left(\frac{1}{R_a} - \frac{1}{R_g}\right)}$$

(9) $$= \frac{1}{1-B}\left(\frac{T_2 - T_{g_1}}{T_{g_1}}\right)$$

or for small temperature differences:

(10) $$\frac{\Delta L}{L} = -\frac{1}{1-B}\left(\frac{\Delta T}{T}\right)$$

the negative sign indicating a loss of lift.

From this equation we may approximate the amount of ballast required to compensate for the loss of superheat of the lifting gas. It is apparent, then, that the amount of superheat gained or lost by a balloon's gas is of extreme importance to the control of the flight.

For this reason a transparent film has a definite advantage over a reflecting fabric. For example, aluminum-coated fabric balloons floating at 40,000 feet have exhibited lifting gas superheat in the neighborhood of 40°C.* Polyethylene balloons, on the other hand, show superheat of approximately 10°C under the same conditions.

Assuming a total weight of 30 kilograms in the balloon system, with helium as the lifting gas ($B \approx \frac{1}{7}$), the following compensation at sunset, or when superheat is lost, will be necessary:

Aluminized fabric:

$$\frac{\Delta L}{L} = \frac{1}{1-\frac{1}{7}}\left(\frac{40^\circ}{250^\circ}\right) = 18.7\,\%$$

Polyethylene:

$$\frac{\Delta L}{L} = \frac{1}{1-\frac{1}{7}}\left(\frac{10^\circ}{250^\circ}\right) = 4.7\,\%$$

*This will explain the rapid descent of flight with fabric balloons and will show the need for high rates of ballast flow at sunset with polyethylene balloon flights (see Part III, "Summary of Flights," of this report).

This relationship between loss of lift and loss of superheat is substantiated by analysis of Flight 94. From the rate of descent the unbalance (using the equation of Clarke and Korff, see page 33) is in the neighborhood of 5 kilograms. Although there was no temperature measurement on this flight, a previous flight of this type indicated a superheat of approximately 40°C. By equation (10), with a gross load of 52 kg., the unbalance caused by loss of all of this superheat would be 9.7 kg. It is believed that ventilation past the balloon during a low velocity descent before operation of the ballast mechanism caused loss of superheat. Since this loss caused greater descent, and thus more ventilation, superheat was lost. An enormous rate of ballast flow would have been required to check descent.

D. Adiabatic Lapse Rate

One of the causes of temperature difference between the lifting gas and free air during rise or descent of balloon systems is the difference in lapse rates of air and the lifting gas. The adiabatic lapse rate is that temperature change caused by adiabatic expansion or compression of a gas during ascent or descent through a given vertical distance. The actual lapse rate of the lifting gas is the adiabatic lapse rate plus the effects of conduction and radiation. The adiabatic lapse rate is defined as:

(1) $$LR = \frac{Ag}{C_p}$$

where:

$A = 2.39 \times 10^{-8}$ cal / erg

C_p = specific heat at constant pressure

g = acceleration caused by gravity

In the metric system for helium, ($C_p = 1.25 \frac{cal}{°C/gm}$):

$$LR = -\frac{980 \times 2.39 \times 10^{-3}}{1.25} = -1.87\,°C/km$$

or:

$$LR = -.57°C/_{1000\ ft}$$

The adiabatic lapse rate for air, ($C_p = 0.239 \frac{cal}{°C/gm}$):

$$LR = -\frac{980 \times 2.39 \times 10^{-3}}{0.239} = -9.8\,°C/km$$

or:

$$LR = -2.98°C/_{1000\ ft}$$

The actual atmospheric distribution, however, does not indicate an adiabatic lapse rate for air but rather a lapse rate which varies with altitude. For the troposphere the lapse rate of the atmosphere averages -1.98°C/1000 ft. It may be shown then that in the troposphere a rising balloon will get warm with respect to the air (neglecting ventilation and radiation effects) at a rate of 1.98 - .57 = 1.41°C/1000 ft. In the tropopause the lapse rate of the atmosphere is zero. Thus the lifting gas (if helium) will cool relative to the air at a rate of .57°C/1000 ft.

Similarly, in the stratosphere, the lifting gas will cool relative to the air at a rate of 2.24 + .57 = 2.81°C/1000 ft. This effect is plotted as Figure 22.

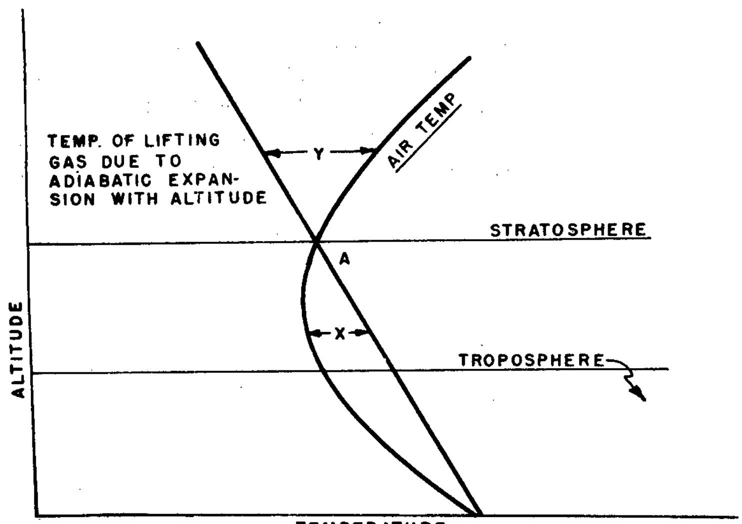


Figure 22. Lapse rate of air and helium.

Here, below point A, the lifting gas will be warmer than the air. Above point A, the lifting gas will be cooler than the air. The effect of this temperature difference on the lift (as shown in the previous section) is approximately $\Delta L = L \frac{\Delta T}{T} \frac{1}{(1-B)}$

Thus, as a balloon system passes through point A, it will have less lift than at release. This effect has been observed on several flights, where a balloon system slowed down during ascent through a temperature inversion.

Since the effect of the sun in heating the lifting gas decreases the effect of different lapse rates, the effect is not as noticeable during the day as at night. At night the balloon system may pass through an inversion, lose its lift, and remain at an altitude much below its estimated floating altitude until warmed by the sun's rays at sunrise.

This effect adds to the stability of stratospheric balloon flights. If a system in equilibrium in the stratosphere were to lose lift and descend, the compression of the gas would cause an increase of the lifting gas temperature relative to the air temperature, causing a decrease in unbalance.

Similarly, an initial unbalance causing rise of the system would cause relative cooling of the lifting gas and thus again decrease the unbalance. Hence, the rate of rise or descent in the stratosphere will be limited by the rate of heat exchange due to conduction and radiation, which will counteract this effect of adiabatic heating or cooling.

Empirical evidence indicates that there is a great deal more stability in a stratospheric balloon system than in a similar system floating in the troposphere. This "adiabatic stability" is a principal reason for better performance of stratosphere flights.

E. Diffusion and Leakage of Lifting Gas

The lifting gas of a balloon can be lost by:

leakage through small holes in the fabric or film;
solution, migration and evaporation through fabric or film;
true molecular diffusion through openings, such as the appendix opening.

(1) Leakage

Volumetric flow, Q, of a gas through any given opening in the balloon surface may be evaluated as a function of the area of the opening, A; the pressure head causing the flow, h; and a coefficient of leakage, C_d.

(1) $$Q = C_d A \sqrt{2gh}$$ where g is the acceleration due to gravity

It would be difficult to evaluate the amount and area of holes in the balloon surface. Let us, then, compare the rate of leakage at any given altitude with leakage at sea level, rather than attempting to evaluate the leakage at a given altitude.

First we shall compare the rate of leakage of a full balloon at any given altitude with leakage of a full balloon at sea level. Let us assume that the area of any opening in the surface of the balloon does not vary with altitude and that the coefficient of leakage is constant. Thus:

(2) $$Q \propto \sqrt{h}$$ where h is pressure head in feet of lifting gas

However:

(3) $$h = \frac{\Delta p}{d_g} \times 144$$

where Δp is the pressure difference across the opening (psi) and d_g is density of lifting gas (lb./ft.^{3}). Combining equation (2) and equation (3):

(4) $$Q \propto \sqrt{\frac{\Delta p}{d_g}}$$

The pressure difference across any given opening can be evaluated in terms of: height above a known point of zero pressure difference; rate of pressure change with altitude of the atmosphere (which, for any small section of altitude is assumed to be constant); and ratio of the densities of air and the lifting gas. Since the pressure difference across the appendix opening is zero this is our reference point for evaluating height. Figure 23 shows this pressure relationship in graphic form.

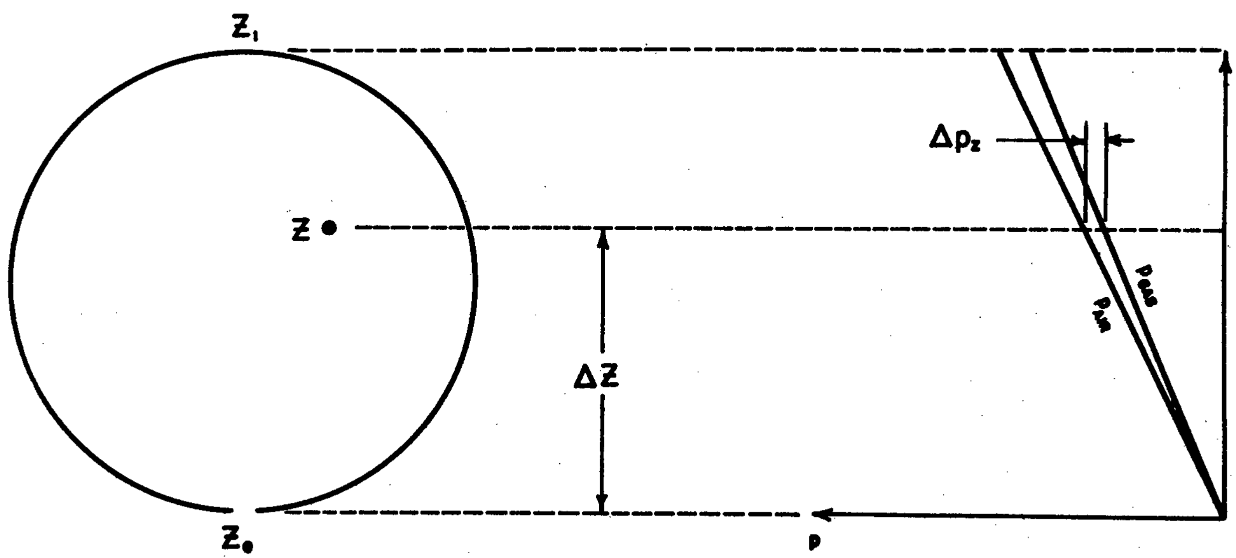


Figure 23. Pressure difference across balloon.

This relationship is expressed as:

(5) $$\Delta p = \Delta z \left(\frac{dp}{dz}\right)_{air} (1-B)$$

where $B = \frac{M_g}{M_a}$, M_g & M_a are molecular weights of lifting gas and air, respectively.

Since, for a full balloon, Δz is constant at any altitude, and B (for our discussion) is a constant:

(6) $$Q \propto \sqrt{\frac{\left(\frac{dp}{dz}\right)_{air}}{d_g}}$$

The mass rate of flow is equal to the density of the lifting gas multiplied by the volumetric rate of flow:

(7) $$L = Q d_g \propto \sqrt{\left(\frac{dp}{dz}\right)_{air} d_g}$$

Since the number of openings will not change with altitude, equation (7) expresses the relationship for mass rate of flow from a full balloon for any altitude. The leakage at any altitude may be expressed as a function of leakage at sea level:

$$\frac{L_z}{L_o} = \left(\frac{\left(\frac{dp}{dz}\right)_{air-z}}{\left(\frac{dp}{dz}\right)_{air-o}} \quad \frac{d_{g_z}}{d_{g_0}} \right)^{\frac{1}{2}}$$

As an example, let us compare the leakage rates of a lifting gas through a full balloon at sea level, at 40,000 feet and at 100,000 feet.

Altitude	$(dp/dz)_{air}$	d_g
0	$\frac{1}{27}$	$\frac{1013}{288R}$
40,000	$\frac{1}{112}$	$\frac{188}{218R}$
100,000	$\frac{1}{1880}$	$\frac{10.9}{218R}$

Comparing rate of leakage at 40,000 feet with leakage at sea level:

$$\frac{L_{40}}{L_0} = \sqrt{\frac{27}{112} \cdot \frac{188}{1013} \cdot \frac{288}{218}} = 0.243$$

Comparing rate of leakage at 100,000 feet with leakage at sea level:

$$\frac{L_{100}}{L_0} = \sqrt{\frac{27}{1880} \cdot \frac{10.9}{1013} \cdot \frac{288}{218}} = 0.044$$

Therefore, if leakage of a full balloon at sea level is known, it is possible to compute theoretical leakage at any altitude. However, if it is not possible to completely inflate a balloon on the ground in order to make a sea level test (if lift would be great enough to rupture balloon or load lines), a method of comparing full balloon leakage with partially full balloon leakage must be found.

Let us assume that it is possible to obtain results of a leakage test for a balloon inflated to a volume $\frac{1}{x}$ of full balloon volume. Again starting with equation (1):

$$Q = C_d A \sqrt{2gh}$$

We see that in this case the total area of openings, A is not constant but is a function of volume. Therefore, we have:

$$Q \propto A\sqrt{h} \tag{8}$$

We have shown that:

$$h = \frac{\Delta p}{d_g} \cdot 144 = \frac{\Delta z \left(\frac{dp}{dz}\right)_{air} (1-B)}{d_g} \cdot 144$$

Since we are comparing partially inflated balloon leakage at sea level with full balloon leakage at sea level the variable in the above expression is Δz. This is graphically illustrated in Figure 24.

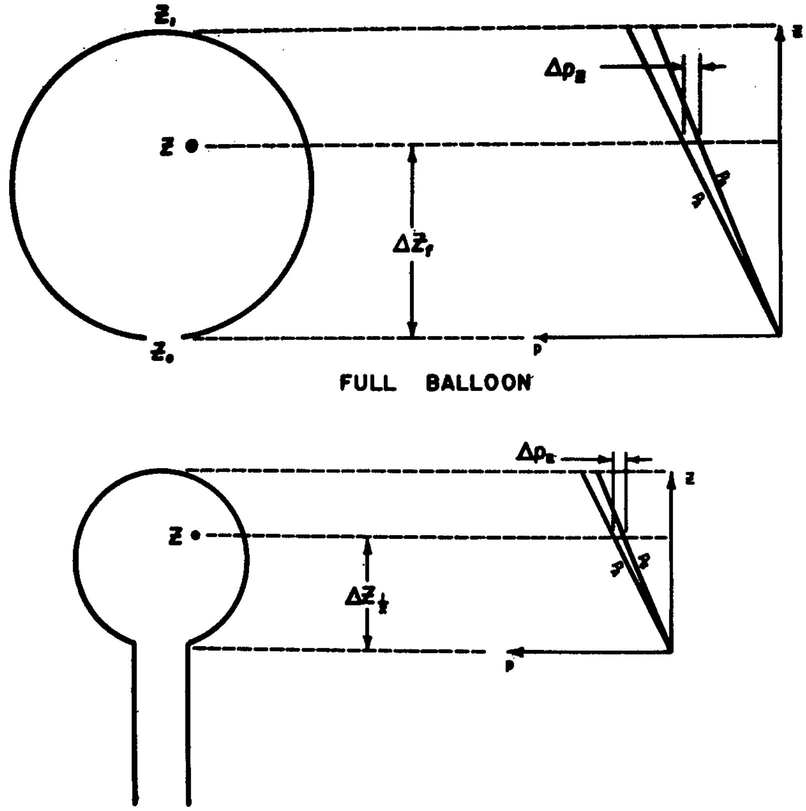


Figure 24. Comparison of pressure head across partially and fully inflated balloons.

Thus, the relationship is:

(9) $$Q \propto A\sqrt{\Delta \bar{Z}}$$

(10) $$Q \propto V^{\frac{2}{3}} \sqrt{V^{\frac{1}{3}}} \propto V^{\frac{5}{6}}$$

Since the density of the lifting gas is constant, we may then express mass leakage as:

(11) $$L \propto V^{\frac{5}{6}}$$

And then, to compare leakage of a full balloon with leakage of a balloon $\frac{1}{x}$ full:

(12) $$L_F = L_{\frac{1}{x}} (X)^{\frac{5}{6}}$$

Example: If a 20-foot diameter balloon $\frac{1}{10}$ full were tested at sea level and found to have a leakage rate of 50 gm/hr. the leakage rate of a full 20-foot balloon at sea level would be:

$$L_f = 50 \frac{GM}{HR} (10)^{\frac{5}{6}} = 340 \frac{GM}{HR}$$

The leakage of a full 70-foot diameter balloon at sea level in this case would be:

$$L_f = 50 \frac{GM}{HR} \left[10\left(\frac{70}{20}\right)^3\right]^{\frac{5}{6}} = 7820 \text{ GM/HR}$$

Values for leakage at several different altitudes for 20-foot and 70-foot diameter balloons, assuming a leakage of 50 gm/hr. for a 20-foot balloon $\frac{1}{10}$ full at sea level are:

Altitude (MSL)	0	40,000 ft.	100,000 ft.
20-ft. diam.	340 gm/hr.	83.2 gm/hr.	15 gm/hr.
70-ft. diam.	7820 gm/hr.	1912 gm/hr.	345 gm/hr.

Another consideration is that relationship expressed by the kinetic theory of gases regarding gases at low pressures. The kinetic theory states that there is a molecular type of flow across a thin diaphragm through openings whose dimensions are of the order of the length of the mean free path of the molecules involved. Mass flow of the gas is then:

$$L = \Delta p \cdot A \sqrt{\frac{d_g}{2\Pi}}$$

where:

Δp = is the pressure difference across the film

A = area of the opening

d_g = density of the gas in question

This relationship, however, becomes valid only at extremely low pressures, and when considering balloon systems at normal floating levels the more common fluid-flow relationship will control the rate of loss of lift through openings in the film. It would be of little use then to investigate further the leakage of gas through openings by means of the relationships involved in the kinetic theory.

(2) Solution, Migration and Evaporation through Film

A very slight amount of lift is lost through solution of the gas into the balloon film, migration through the film and evaporation into the atmosphere. The rate of this type of diffusion is a function of the characteristics of the lifting gas and the partial pressure involved. Since the lifting gas is assumed to be very nearly pure, the partial pressure is merely the pressure of the atmosphere in which the balloon is floating. This method of diffusion need not be considered when examining the loss of a balloon's lifting gas since it is of a low enough value to be insignificant as compared with the loss of gas by leakage through openings in the film.

Tests have indicated that this type of diffusion through .001" polyethylene has a value of approximately 4 liters/meter^2/day. At sea level this is equivalent to 5.32 gm/hr. for a 20-foot diameter balloon. At 40,000 feet MSL the value would be approximately 1 gm/hr.

(3) Diffusion through Appendix

We have seen that there is no pressure difference across the open appendix of the balloon during floating. Therefore, the loss of lifting gas through this appendix (except when the balloon is rising and gas is being valved out of the appendix) can be only by true intermolecular diffusion of the gas into the atmosphere and air into the lifting gas. The expression for loss of lifting gas by diffusion is similar in form to the expression for transfer of heat through a given distance by conduction:

$$(13) \qquad \frac{dN}{dt} = -D\frac{dN}{dz}\,dy\,dx$$

where:

$\frac{dN}{dt}$ = time rate of transfer of molecules of gas across the area $dy\,dx$ in direction z

D = a coefficient of diffusion, dependent upon viscosity and density of the gas involved $(D = c\frac{\eta}{\rho})$

$\frac{dN}{dz}$ = variation of molecular concentration with variation in direction z

$dydx$ = the differential term for area.

Then, since a molecule of lifting gas has a given weight, we may state that:

(14) $$\frac{dw}{dt} = K\frac{dN}{dt}$$

where K is a constant.

We may state the relationship (13) in terms of rate of transfer and area of the opening, assuming $\frac{dN}{dz}$ to be constant across the opening:

(15) $$\frac{dw}{dt} = -K_1 D\frac{dc}{dz}A$$

where:

$\frac{dw}{dt}$ = mass transfer of lifting gas

$\frac{dc}{dz}$ = variation of concentration of lifting gas in direction z

A = area of opening

In order, then, to determine the rate of loss of lifting gas by diffusion through the open appendix we **must**:

(a) determine the relationship between the coefficient of diffusion, D, and altitude (or pressure and temperature)

(b) determine the loss of lift by diffusion through the appendix at any convenient altitude (i.e. at the ground)

(c) derive a relationship between loss at the ground and loss at any altitude.

However, determination of valid relationships to find diffusion through the appendix opening would require large scale laboratory testing and then tedious derivation of mathematical equations, a study in research in itself. It was deemed more practical to reduce or eliminate this type of loss of lift by reduction of the area of the opening by use of a relief valve system as explained in Part II of this report, "Operations," pp. 8-14.

F. Bursting Pressure and Appendix Considerations

Bursting pressure of a balloon can be computed from the equation:

(1) $$\Delta p = \frac{4S_F t}{D}$$ for failure of the fabric or film,

where:

Δp = bursting pressure (psi)

S_f = maximum allowable tensile stress of fabric or film (psi) (for safety $S_f = 1/2\ S_{max}$ where S_{max} = maximum stress in tension)

t = thickness of fabric or film (in.)

D = balloon diameter (in.)

or:

$$(2) \qquad \Delta p = \frac{4 S_s}{D} \qquad \text{for failure of seams}$$

where:

S_s = maximum allowable tensile strength of seams (lb./in.)

D = balloon diameter (in.)

In general, a balloon should be manufactured so that any failure should occur first in the fabric or film and thus the tensile stress of this fabric or film will be the factor in determining bursting pressure.

Since the non-extensible balloons used in constant-level work by the N.Y.U. group have been of the open-appendix type, bursting due to excessive super-pressure has not been a problem. Strength of the balloon must be considered, however, from the standpoints of back pressure induced during rise of a full balloon and pressure distribution of the lifting gas itself inside of the balloon.

(1) Pressure Distribution of Lifting Gas

It was shown in the previous section that the pressure difference across any portion of the balloon surface may be equated:

$$(3) \qquad \Delta p_z = \Delta z \frac{dp}{dz} (1 - B)$$

A plot of Δp against Δz would then be a straight line at any given altitude. Maximum allowable balloon pressure--equation (1)--may be plotted as a function of Δz , rather than diameter for any given horizontal plane of the balloon surface, z . Using this relationship, cutting any horizontal plane $z-z$ across the balloon (Figure 25), the diameter of the balloon at any point z may be expressed as:

$$d_z = 2\left[\left(\frac{D}{2}\right)^2 - \left(\Delta z - \frac{D}{2}\right)^2\right]^{1/2}$$

(4) $$= 2\left[D\Delta z - \Delta z^2\right]^{1/2}$$

Therefore, maximum allowable balloon pressure at any plane $z-z$ will be:

(5) $$\Delta p_z = \frac{4 S_f t}{2(D\Delta z - \Delta z^2)^{1/2}} \text{ psi}$$

Equation (5) may be plotted in terms of bursting pressure and Δz for any given diameter balloon. A straight line through the origin and tangent to the plot of Equation (5) will indicate the maximum allowable $(dp/dz)_{air}$ $(1-B)$ for any given diameter balloon. Comparing the maximum allowable $(dp/dz)_{air}$ with a chart of altitude vs. pressure in the atmosphere will indicate the minimum altitude at which the balloon can be allowed to be full. From an altitude-buoyancy table for any given diameter balloon, the maximum allowable buoyancy, or maximum allowable gas inflation can be obtained.

Figure 26 is a plot of equations (3) and (5) for .001" polyethylene ($S_f = \frac{900}{2}$ psi) balloons of 20', 30' and 70' diameters.

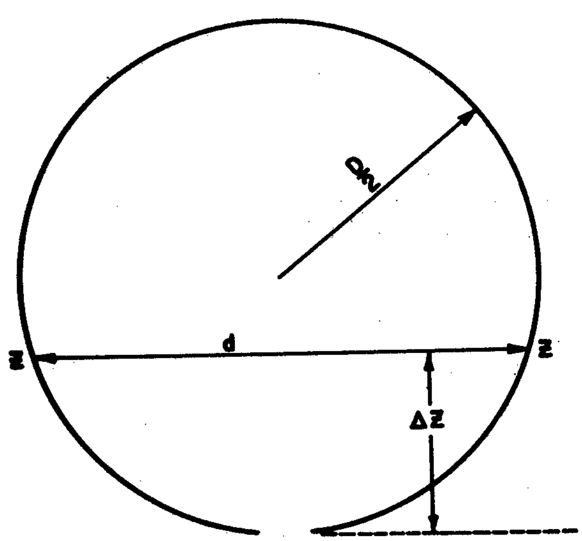


Fig. 25.
Relationship d/ΔZ, for balloon.

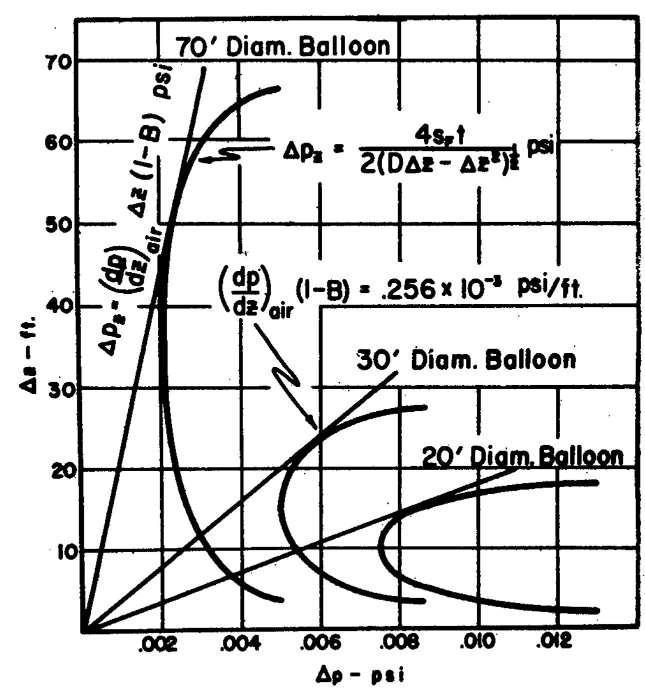


Fig. 26.
Graph of equations (3) and (5).

We see that the maximum allowable $(dp/dz)_a(1-B)$ for a 30' diameter, .001" thick polyethylene balloon is 256×10^{-3} psi/ft . Dividing by (1-B) we have the maximum allowable:

$$(dp/dz)_a = \frac{256 \times 10^{-3}}{1-.138} = .300 \times 10 \quad psi/ft^{-3}$$
$$= 20.7 \times 10^{-3} \quad mb/ft$$

This is comparable to an altitude of 18,300 ft. or a gross buoyancy of 450 lb., the maximum allowable inflation of a 30' diameter, .001" thick polyethylene balloon from the standpoint of pressure distribution.

In order to determine mathematically the point of failure due to pressure distribution we may use equations (3) and (5) and their derivatives:

$$\Delta p_z = \Delta z \left(\frac{dp}{dz}\right)_{air} (1-B)$$

$$\Delta p_z = \frac{4Sft}{2(D\Delta z - \Delta z^2)^{1/2}}$$

at the point of tangency of these curves (T in Figure 26):

$$\Delta p_{T3} = \Delta p_{T5} \quad \text{and} \quad \left(\frac{dp}{dz}\right)_{T3} = \left(\frac{dp}{dz}\right)_{T5}$$

in equation (5), making $\frac{4Sft}{2} = K$ and in equation (3), making $(dp/dz)_a(1-B) = m$, the slope of the line $\Delta p_z = \Delta z \cdot m$ we have:

$$\text{(5a)} \qquad \Delta p_z = \frac{K}{(D\Delta z - \Delta z^2)^{1/2}}$$

and:

$$\text{(3a)} \qquad \Delta p_z = m\Delta z$$

differentiating with respect to z :

$$\text{(5b)} \qquad \frac{dp}{dz} = -\frac{K}{2}\frac{(D-2\Delta z)}{(D\Delta z - \Delta Z^2)}$$

$$\text{(3b)} \qquad \frac{dp}{dz} = m$$

Since at T, $\left(\frac{dp}{dZ}\right)_3 = \left(\frac{dp}{dZ}\right)_5$:

$$m = -\frac{K}{2}\,\frac{(D-2\Delta Z)}{(D\Delta Z-\Delta Z^2)^{3/2}}$$

and, since at T, $\Delta p_{Z3} = \Delta p_{Z5}$:

$$m\Delta Z_T = -\frac{K\Delta Z_T}{2}\,\frac{(D-2\Delta Z_T)}{(D\Delta Z_T-\Delta Z_T^2)^{3/2}} = \frac{K}{(D\Delta Z_T-\Delta Z_T^2)^{1/2}}$$

and:

$$\Delta Z_T\,(2\Delta Z_T - D) = 2(D\Delta Z_T - \Delta Z_T^2)$$

$$\Delta Z = \tfrac{3}{4} D$$

Then:

$$\Delta p_T = \frac{K}{\left(\frac{3}{4}D^2-\frac{9}{16}D^2\right)^{1/2}} = \frac{K}{\sqrt{\frac{3}{4}}\,D}$$

$$m = \left(\frac{dp}{dz}\right)_{air}(1-B) = \frac{K(2\cdot\frac{3}{4}D-D)}{2\left(\frac{3}{4}D^2-\frac{9}{16}D^2\right)^{3/2}} = \frac{16K}{3\sqrt{3}\,D^2}$$

Allowable:

$$\left(\frac{dp}{dz}\right)_{air} = \frac{16K}{3\sqrt{3}\,D^2}\cdot\frac{1}{1-B}$$

For the example above,

$D = 30'$, $S_f = \frac{900}{2}$, $t = .001$ in., $B = \frac{53.3}{386} = 0.138$ (helium)

Then:

$$\left(\frac{dp}{dz}\right)_{air} = \frac{16}{3\sqrt{3}}\cdot\frac{4}{2}\cdot\frac{900}{2}\cdot\frac{.001}{(30)^2\cdot 12}\cdot\frac{1}{(1-0.138)} \quad psi/ft$$

Allowable $\left(\frac{dp}{dz}\right)_{air} = 0.298\cdot 10^{-3}$ psi / ft

$= 20.55$ mb/ft

This is comparable to an altitude of approximately 18,200 ft. Thus the maximum allowable buoyancy for a 30' diameter, .001" thick polyethylene balloon filled with helium is 440 lb.

(2) Appendix-Opening Considerations

As an open-appendix, constant-volume balloon ascends the lifting gas will expand due to the decrease in the pressure of the surrounding atmosphere. Upon reaching the altitude at which it is full it will still have an unbalance in the direction of increase of altitude due to the excess buoyancy causing ascent. This unbalance is gradually decreased as the balloon rises (with a fixed volume) into less dense air. Meanwhile excess gas pressure is relieved by valving gas through the appendix until the balloon system is in a condition of equilibrium. The portion of the ascent after the balloon has become full is known as the "leveling-off" period.

The lifting gas which is valved out through the appendix will cause a "back pressure" inside of the balloon which must be transferred to the balloon fabric or film. In other words, there must be a pressure difference across the appendix opening during this period to force the excess lifting gas out of the balloon. Let us analyze this back pressure by the method used by Picard. Using the rules of subsonic aerodynamics, Picard suggests that air at sea level escaping at 1333 ft/sec. produces a back pressure of 1 atmosphere and that back pressure induced is proportional to the square of escape velocity of the gas and inversely proportional to the density of the gas escaping. Volume of gas lost in ascent through 1 foot is, within a reasonable degree of accuracy:

(6) $$\frac{\Delta V}{\Delta Z} = \frac{V}{P}\frac{dp}{dz}\cdot\frac{T+\Delta T}{T}$$

$\frac{\Delta V}{\Delta Z}$ = volume lost per foot of ascent (ft.^{3}/ft.)

V = balloon volume (ft.^{3})

P = pressure of free air (psi)

$\frac{dp}{dz}$ = pressure change with increase of Z (psi/ft)

T = temperature of air (°C abs.)

ΔT = change in air temperature during rise (°C)

For ascent in the troposphere this relationship will reduce to:

(7) $$\frac{\Delta V}{\Delta Z} = \frac{V}{27{,}800}\ \frac{FT^3}{FT}$$

The velocity of escape of gas, then:

(8) $$V = \frac{dz}{dt}\cdot\frac{V}{27{,}800}\cdot\frac{1}{A_a}$$

V = velocity of escape of lifting gas (ft./sec.)

$\frac{dz}{dt}$ = ascent velocity of balloon (ft./sec.)

$\frac{V}{27800}$ = volume of gas lost per foot of ascent (ft.^{3}/ft.)

A_a = area of appendix opening (ft.^{2})

The back pressure caused by this velocity:

$$(9) \qquad \Delta p = \left(\frac{V}{1333}\right)^2 \cdot 14.7 \frac{d_g}{d_{ao}}$$

Δp = back pressure induced (psi)

V = velocity of escape of gas (ft./sec.)

d_g = density of lifting gas at altitude of balloon (lb./ft.^{3})

d_{ao} = density of air at sea level (lb./ft.^{3})

14.7 = pressure of air at sea level (psi)

1333 = escape velocity of air to produce back pressure of 1 atmosphere at sea level (ft/sec)

or, combining equation (8) and (9):

$$(10) \qquad \Delta p = \frac{\left(\frac{dz}{dt} \cdot \frac{V}{27800} \cdot \frac{1}{A_a}\right)^2}{(1333)^2} \cdot 14.7 \frac{d_g}{d_{ao}} \quad \text{psi}$$

As an example, let us find the back pressure induced in a 20' diameter balloon with a 1' diameter opening ascending at 800 ft./minute, as it becomes full at 30,000 ft. (density of helium @ 30,000 ft. = $\frac{300}{1013} \cdot \frac{290}{232} \cdot 0.138\ d_{a_0}$)

$$\Delta p_{20} = \frac{\left(\frac{800}{60} \cdot \frac{\pi \cdot 20^3}{6 \cdot 27800} \cdot \frac{4}{\pi}\right)^2}{1333^2} \cdot 14.7 \cdot 0.051 = .275 \times 10^{-4} \text{psi}$$

It is to be noted that equation (5) can be arrived at by more simple reconstruction of the standard equation for fluid flow:

$$(11) \qquad \frac{dV}{dt} = C_d A_a \sqrt{2gh}$$

$\frac{dV}{dt}$ = volume rate of flow (ft.^{3}/sec.)

C_d = a constant of flow

g = the acceleration of gravity (ft./sec.^{2})

A_a = area of the opening (ft.^{2})

h = head of fluid causing flow (ft.)

since $h = \dfrac{144\,\Delta p}{d_g}$, we have:

(12) $$\Delta p = \frac{d_g}{288g}\left(\frac{1}{C_d A_a}\cdot\frac{dV}{dt}\right)^2 \quad psi$$

where d_g is density of the lifting gas (lb./ft.^{3}).

From equation (7) we have:

$$\frac{dV}{dt} = \frac{dz}{dt}\,\frac{V}{27800} \quad ft^3/sec$$

therefore:

(13) $$\Delta p = \frac{d_g}{288g}\left(\frac{1}{C_d A_a}\quad\frac{dz}{dt}\cdot\frac{V}{27800}\right)^2 \quad psi$$

Comparing equations (10) and (13) we see that if the equations are equal:

$$\frac{1}{288g\,C_d^2} = \frac{14.7}{1333^2\,d_{ao}}$$

If we let $C_d = .975$, a reasonable value for the relatively low velocity flow of gas through the appendix, we have:

$$\frac{1}{288g\,C_d^2} = 113.5 \times 10^{-6} \text{ ft-sec}^2/\text{in}^2$$

$$\frac{14.7}{1333^2\,d_{ao}} = 114.8 \times 10^{-6} \text{ ft-sec}^2/\text{in}^2$$

Therefore, the equations (10) and (13) are equal and interchangeable.

It may be noted from equations (10) and (13) that for any given balloon, appendix area and balloon volume are fixed, and the related variables are lifting gas density, rate of rise, and allowable back pressure. For any given allowable back pressure greater rates of rise are allowable at higher altitudes (where d_g is lower).

Once a floating altitude has been decided upon or it has been decided to carry a given load as part of the balloon system, we can find a maximum allowable rate of rise. We must consider the pressure distribution of the lifting gas and the internal back pressure due to valving gas. To find maximum rates of ascent for various balloons would necessitate a complicated series of trial and error solution. In general, it has been more practical to determine a maximum rate of rise for normal operating conditions for any given size balloon by finding the maximum allowable rate for the balloon rising to its lowest normal operating level (i.e., we will find the maximum allowable rate for the worst normal operating conditions and consider it a maximum for all normal operating conditions.)

Let us take the case of a 20-foot diameter polyethylene balloon of .001" thickness. Lowest normal floating altitude is 20,000 ft. MSL. Let us assume that the balloon will be full and begin valving gas at 15,000 ft. MSL. Assume the appendix diameter to be $\frac{1}{2}$ foot. Using equation (1) to find maximum allowable internal pressure and assuming the critical x-y plane to be that of maximum diameter $\Delta Z = D/2$, we have:

$$\Delta p_{all.} = \frac{4 S_f t}{D} = \frac{4(900/2)\cdot .001}{12\cdot 20} = .0075 \text{ psi}$$

(Here we have introduced a factor of safety by saying $S_f = 900/2$ instead of 900 psi, the ultimate strength in tension of polyethylene.) Pressure distribution:

$$\Delta p_{D/2} = \Delta Z \frac{dp}{dZ}(1-B) = \frac{20}{2}\cdot 3.38\cdot 10^{-4}\cdot .862 = .00291 \text{ psi}$$

Allowable back pressure:

$$\Delta p_{bp} = \Delta p_{all} - \Delta p_{D/2} = .0046 \text{ psi}$$

Maximum rate of rise using equation (13);

$$\frac{dZ}{dt} = \sqrt{\frac{288\,\Delta p_{bp} g}{d_g}} \left(\frac{27800}{V} C_d A_a\right) \text{ft/sec}$$

$$= 100.7 \text{ ft/sec}$$

$$= 6000 \text{ ft/min}$$

It is evident from this calculation that the rate of rise of the 20-ft. diameter polyethylene balloon is not a critical factor in bursting unless the open appendix becomes snarled and gas is not allowed to escape.

Rate of rise and appendix openings are important from the standpoint of balloon design. For operational reasons it is important to have a rapid rate of rise. In order to make most efficient use of weight, the balloon film should be thin. As mentioned in the preceding section on diffusion and leakage the appendix opening should be small. It can be seen that as we make one of our conditions better, we must sacrifice at least one of the others. Therefore, balloons must be designed compromising rate of rise, balloon thickness, and appendix opening. Methods of decreasing the appendix opening, except during the valving of lifting gas, are discussed in other sections of this technical report. In general they consist of means of applying a delicate relief valve, capable of opening to a large area with application of only slight internal pressure, and also closing tight upon release of this internal pressure.

G. A General Equation of Motion

If we collect and relate the variables incidental to balloon flight, we may form a general equation of motion. This is most easily expressed in terms of forces acting upon the balloon system. We may equate an acceleration term plus a drag or friction term against a term to include all other forces:

$$(1) \qquad m D^2 z + n (Dz)^2 = \Sigma F$$

This is a differential equation of a type common in mechanical vibration problems, and solution for the variable z would not be difficult if relationships of the many variables included in the the terms n and ΣF were simple. However, the complexity of the balloon system introduces many terms as parts of n and ΣF.

We shall first state the more complex form of equation (1) above and then attempt to explain the variables included in each part of the equation. As will be shown, it is extremely difficult to find a complete solution of the equation since many of the variables are in themselves extremely complex and at this time incapable of accurate solution. Therefore, our discussion will be more of a qualitative rather than a quantitative nature.

The general force equation is:

$$(2) \qquad \frac{W}{g} D^2 z + C \frac{\rho}{2} A (Dz)^2 = V_b (\rho_a - \rho_g) - W \pm F_{atm}$$

The force due to acceleration $F_A = \frac{W}{g} D^2 z$
where:

W = weight of the balloon system

g = acceleration of gravity

$D^2 z$ = acceleration of the balloon system (An acceleration in the direction of greater altitude is considered positive.)

The force due to friction or drag $F_D = C_D \frac{\rho}{2} A\, Dz$ (This assumes that there is no vertical motion of the air in which the balloon system is floating. We shall later consider the case where an atmospheric force is causing vertical motion of the air.)
Where:

ρ = mass density of the air surrounding the balloon system

A = projected area of the balloon on a plane perpendicular to the relative velocity

Dz = vertical velocity of the balloon system (Velocity in the direction of greater altitude is considered positive.)

C_D = a coefficient of drag, dependent on Reynolds number $N_R = \frac{Dz\, d\, \rho}{\mu}$ where:

d = diameter of sphere (ft.)

ρ = mass density of surrounding fluid $\left(\frac{\text{lb. sec.}^2}{\text{ft.}^4}\right)$

μ = viscosity of surrounding fluid $\left(\frac{\text{lb. sec.}}{\text{ft.}^2}\right)$

A plot of drag coefficient against Reynolds number for a sphere is shown in Figure 27.

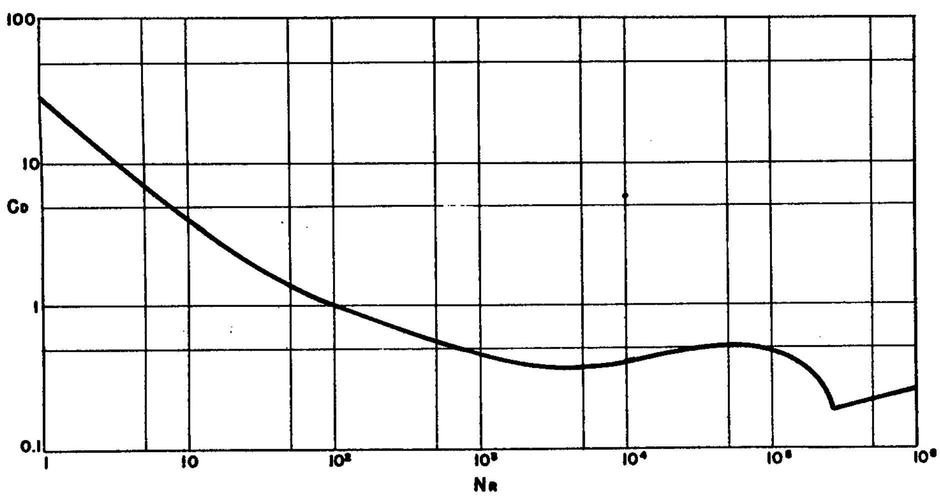


Figure 27. Drag coefficient vs. Reynolds Number, for sphere.

If a balloon is teardrop in shape rather than spherical, the curve would be modified so that the value of C_D, for a given Reynolds number would be lower. In this case the sudden drop in C_D as Reynolds number increases (the change from viscous to turbulent flow) would occur at a lower Reynolds number.

We have thus far in our discussion assumed that there is no vertical motion of the air surrounding the balloon system relative to the coordinate z. However, this is not necessarily the case under actual conditions. In many instances vertical air movement is found in the atmosphere. Therefore, we must introduce a term to allow for this vertical air movement. In equation (2) this term was indicated as $\pm F_A$, the external atmospheric force.

We may consider this vertical air movement in terms of a velocity $D\zeta$. Then the vertical velocity of the balloon system relative to the air surrounding the system will be the difference between the velocity of the balloon relative to the absolute altitude Dz and the velocity of the surrounding air relative to the absolute altitude This may be equated as $Dz - D\zeta$, where Dz and $D\zeta$ are both considered positive in the direction of increase of altitude.

The total force due to the drag, or friction will be:

$$F_D + F_{ATM} = C_D \frac{\rho}{2} A (Dz - D\zeta)^2$$

where the notations are those used previously, except that now $N_R = \frac{(Dz - D\zeta)\, d\rho}{\mu}$. The relationship between N_R and C_D will be those used previously.

The force due to buoyancy of the lifting gas $F_B = V_b\,(\rho_a - \rho_g)$ where:

V_b = balloon volume (ft.^{3})

ρ_a, ρ_g density of the air and lifting gas, respectively (lb./ft.^{3})

This term may also be stated as: $F = V_b \left(\frac{p_a}{R_a T_a} - \frac{p_g}{R_g T_g} \right)$
where:

p_a, p_g = pressure of air and lifting gas

R_a, R_g = specific gas constant of air and lifting gas

T_a, T_g = temperature of air and lifting gas

The changes that will take place in this expression are those due to a temperature difference between the lifting gas and the free air, change in volume of the balloon due to loss of lifting gas, change of the gas constant of the lifting gas due to dilution with air, and (in the case of a balloon that will hold an internal pressure) pressure difference between lifting gas and surrounding air.

Temperature effects were discussed previously in this report. Those discussions on superheat and adiabatic temperature change will apply to the general equation. In general, temperature of the free air and lifting gas can be measured to a fair degree of accuracy.

Balloon volume at any time is a function of original full balloon volume plus the summation of all the changes in volume due to pressure and temperature changes and loss of lifting gas. It will also be affected by loss or gain of air by the balloon through diffusion and intake of air through the appendix. The non-extensible balloon will have a maximum volume and thus any changes tending to increase the gas volume to a value greater than the balloon volume will result in a valving of the excess lifting gas into the air, or (in the case of a balloon which will carry internal pressure) a pressure increase of the lifting gas.

It is for this reason that a non-extensible balloon is said to be in a state of stable equilibrium in a direction of greater altitude when it is full. However, in a direction of lesser altitude, and with the case of a partially full floating balloon, the system is in a state of neutral equilibrium.

Composition of the lifting gas will change due to contamination of the lifting gas by the entry of air into the balloon, either by the flow of air through the appendix opening or by diffusion of air into the balloon. We may then modify our term for density of the lifting gas to include a term for the pure gas and a term for the contaminating air. Using the method of partial volumes, we may equate the density of the lifting gas at any time by:

$$\rho_g = \frac{P_g}{V_b T_g}\left(\frac{V_p}{R_p} + \frac{V_a}{R_a}\right)$$

where:

P_g = pressure of the lifting gas

V_b = total lifting gas volume

V_p = volume of pure lifting gas in balloon

V_a = volume of air in balloon

R_g = specific gas constant of pure lifting gas

R_a = specific gas constant of air

Then, calling $\frac{V_p}{V_b} = x_p$ and $\frac{V_a}{V_b} = x_a$ (here we see that since $V_p + V_a = V_b$, $x_p + x_a = 1$) we may equate:

$$\rho_g = \frac{P_g}{T_g}\left(\frac{x_p}{R_p} + \frac{x_a}{R_a}\right)$$

The equation for the force due to buoyancy will then become:

$$F_B = V_b \left[\frac{p_a}{R_a T_a} - \frac{p_g}{T_g} \left(\frac{x_p}{R_p} + \frac{x_a}{R_a} \right) \right]$$

If the balloon is of the type that will carry no internal pressure $p_a = p_g$, and we may state that:

$$F_B = V_b \, p_a \left[\frac{1}{R_a T_a} - \frac{1}{T_g} \left(\frac{x_p}{R_p} + \frac{x_a}{R_a} \right) \right]$$

Discussions of the contamination of the lifting gas are included under the section on "Diffusion and Leakage of Lifting Gas" of this report.

The force due to the weight of the system $F_W = W$ The weight of the balloon system at any time is a function of the original weight of the system plus the change of weight of the system. This change in the weight of the system is caused by the loss of ballast and the weight of the system at any time (t):

$$W_t = W_0 - \sum_{t=0}^{t} \Delta W_b$$

where:

W_0 = the original weight of the system

$\sum_{t=0}^{t} \Delta W_b$ = the sum of all the losses of ballast from time at which $W = W_0$ until the time t

The value of the term $\sum_{t=0}^{t} \Delta W_b$ depends on the type of ballast control. With no ballast:

$$\sum_{t=0}^{t} \Delta W_b = 0 \qquad \text{and} \qquad W_t = W_0$$

If a constant ballast flow is used:

$$\sum_{t=0}^{t} \Delta W_b = \frac{dW}{dt} t$$

where:

$\frac{dW}{dt}$ = rate of ballast flow

t = elapsed time from $t = 0$ to $t = t$

If a practical fixed opening type or ballast control is used:

$$\sum_{t=0}^{t} \Delta W_b = f \, (t, h, \mu_b, \rho_b, A)$$

where:

t = time

h = head of ballast above opening

μ_b = viscosity of ballast fluid

ρ_b = density of ballast fluid

A = area of opening

The ballast flow at any time, t:

$$\frac{dW}{dt} = C_F \rho_b A \sqrt{2gh}$$

so that:

$$\sum_{t=0}^{t} \Delta W_b = \int_0^t C_F \rho_b A \sqrt{2gh}\ dt$$

where:

C_F is a coefficient of discharge, dependent upon Reynolds number of the flow through the opening

In this equation only $\sqrt{2g}$ and A are constants (if temperature effect on the opening A is neglected), ρ_b is dependent upon temperature of the fluid and h is dependent upon the shape of the vessel containing the fluid and time t.

If ballast flow is controlled by atmospheric pressure:

$$\sum_{t=0}^{t} \Delta W_b = \sum_{t=0}^{t} \frac{dW}{dt}\, t_{p>p_c}$$

, with a fixed valve opening (open-or-closed valve)

where $t_{p>p_c}$ represents the time when atmospheric pressure is greater than the pressure of control. Here, again, $\frac{dw}{dt} = C_F \rho_b A \sqrt{2gh}$

With ballast flow proportional to $p - p_c$:

$$\sum_{t=0}^{t} \Delta W_b = \sum_{t=0}^{t} \frac{d\left(\frac{dW}{dt}\right)}{d\Delta p} (p - p_c)\, t_{p>p_c}$$

where:

$\frac{d\left(\frac{dW}{dt}\right)}{d\Delta p}$ relationship between rate of flow and pressure difference ($p - p_c$) where $p > p_c$

If we include a rate of pressure change control or a rate of ascent control such that there is no ballast flow if rate of pressure change is less than some value $-\left(\frac{dp}{dt}\right)_c$ or rate of ascent is greater than some value $\left(\frac{dz}{dt}\right)_c$,we impose the condition for ballast flow in the above two cases that for flow to occur $p > p_c$, and $\frac{dp}{dt} > \left(\frac{dp}{dt}\right)_c$ or $\frac{dz}{dt} < \left(\frac{dz}{dt}\right)_c$

We might also have a control that will open or close a valve on rate of pressure change such that:

$$\sum_{t=0}^{t} \Delta W_b = \sum_{t=0}^{t} \frac{dW}{dt}\, t_{\frac{dp}{dt} > \left(\frac{dp}{dt}\right)_c}$$

where $t_{\frac{dp}{dt} > \left(\frac{dp}{dt}\right)_c}$ is the time during which pressure change of the air surrounding the balloon is greater than a design value of pressure change causing ballast flow.

The general equation, then, indicates the relationships between the variables involved in balloon flight. The discussions in this section of the report, "Equations and Theoretical Considerations," attempt to qualitatively organize the relationships between these variables in order that a complete overall picture of the aspects of balloon flight can be formulated.

It should be stressed that the theoretical relationships as stated here do not lend themselves to simple insertion into an overall equation which is easily solved. Rather, solutions of many of the variables are in themselves complex. At this time it appears impractical to delve too deeply into such matters as "the variation of diffusion and leakage through various types of balloons under different conditions" or "a study in the change of coefficient of drag on a balloon system at all points during its flight." It has been more practical to generally state the relationships in unsolved form and concentrate the experimental portion of the research problem on such matters as actual development of balloon controls.

V. TELEMETERING

A. Information Transmitted

The need for a balloon-borne transmitter and some system of ground receiving and recording was recognized early in the work of the project. The primary objective of such telemetering was to collect data to evaluate the altitude controls applied to the balloon system. Pressure, perhaps the most important data, was measured by the use of radiosonde-type aneroid capsules. A discussion of the pressure modulators used is given in the following section.

A second use of air-borne transmitters was to provide a beacon for radio direction-finding. With proper equipment a balloon-borne transmitter can provide a signal to guide an aircraft, homing with a radio compass, or provide a position "fix" by the crossed azimuths of ground receiving stations.

In addition to these two very important functions of altitude determination and positioning, telemetering systems were used to detect and transmit temperature data and ballast flow data. The equipment used for these purposes is described below.

B. Transmitters Used

(1) 72-Megacycle Radiosonde Transmitter (T-49)

The standard T-49 transmitter of the Army Weather Service was first used in project work, with a modified commutator bar switching specially coded resistors into the circuit as the balloon passed from one critical pressure to another. The operating characteristics of this transmitter may be found in the following publications: T.B. Sig. 165, T.M. 11-2403, T.M. 11-2404 and the Weather Equipment Technician's Manual.

The defects which were encountered in the use of this transmitter were principally (1) relatively short range and (2) unfitness for direction-finding using available equipment. Our experience has been that reception from the T-49 transmitter by standard equipment is not much above 80 miles under good conditions. When flights were made which traveled many times this distances, the inadequacy of this transmitter was clearly demonstrated.

The problem of direction-finding is of major importance when attempts are made to position and track the balloon and its equipment train. Since no standard directional receiver equipment is available for this use with the T-49, this transmitter is of limited value.

(2) 400-Megacycle FM Transmitter (T-69)

The T-49 transmitter was abandoned in favor of the T-69 400-mc system as soon as ground receiving equipment for the latter was available. By using the directional receiving set SCR-658 with the T-69 transmitter, the problem of direction-finding and positioning was attacked. A second advantage enjoyed by this system is the improved range attainable.

Our experience has been that an SCR-658 set in good condition can receive a signal up to a range of 150 miles, providing that the line-of-sight transmitter is high enough to preclude blocking by intervening terrain. The use of two or more sets to increase the area of a tracking net is discussed under "Radio Direction-Finding" below.

The operating characteristics of the T-69 system and the SCR-658 may be found in these publications: T.B. Sig. 165, T.M. 11-1158A.

Pressure indicators were obtained, as with the T-49, by use of the modified commutator bar switching specially coded resistors into the circuit as the balloon passed from one fixed pressure to another. A few special tests were made of a chronometric system of pressure modulation. For a complete discussion of pressure modulation methods, see Section VI, A.

(3) Low-Frequency Transmitter (AM-1)

A low-frequency transmitter developed by the Electrical Engineering Department of New York University was adapted to replace or supplement the T-49 and T-69 transmitters. The carrier frequencies used have been in the region 1 mc to 3 mc. The schematic of this set is shown in Figure 28, as operated at 3135 kc. The output is approximately 2 watts, and a typical air-to-ground range is 300 miles, although reception of more than 450 miles has been attained by both ground and air-borne receivers.

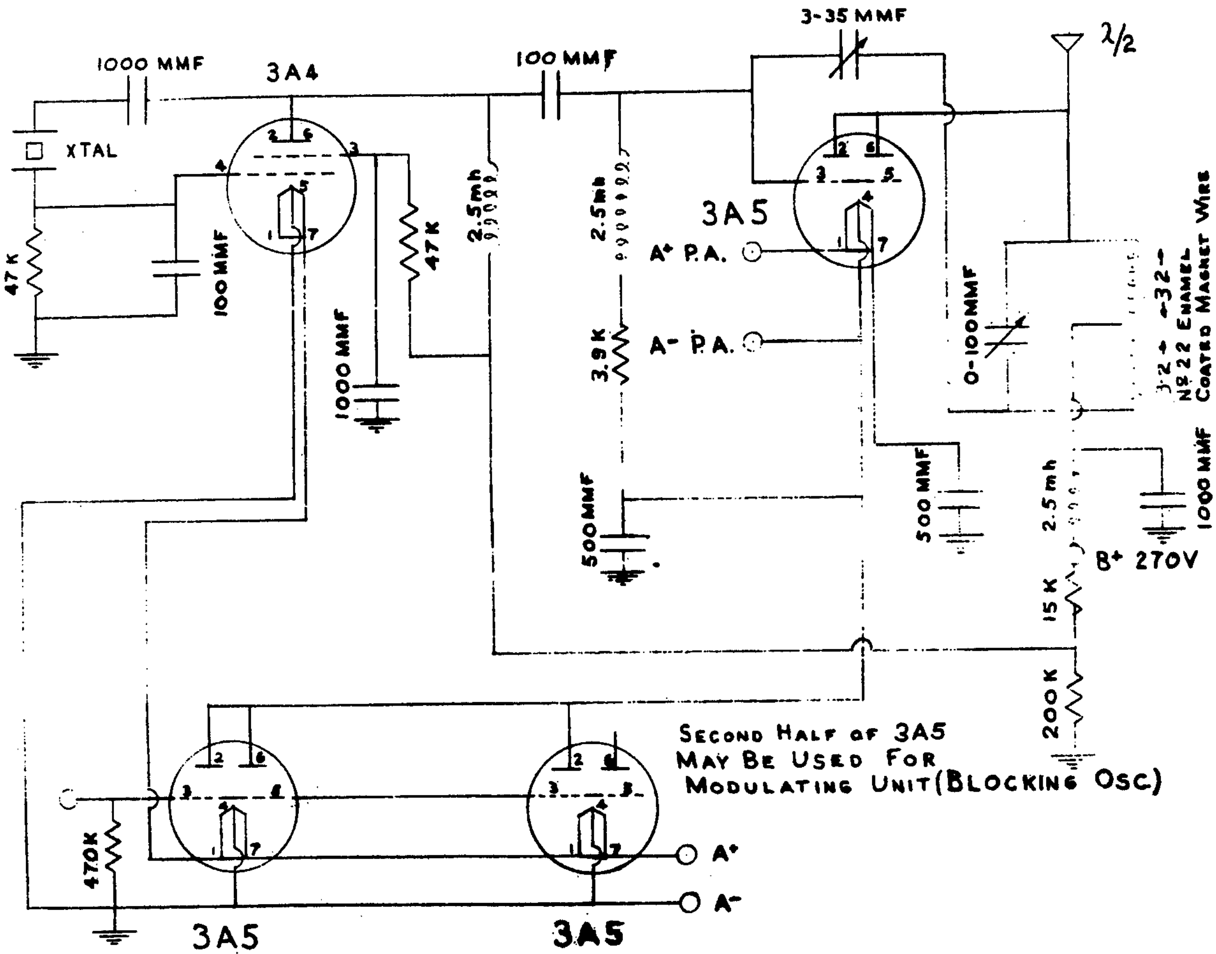


Figure 28. Schematic diagram, AM-1 transmitter.

Information is introduced in a manner similar to that employed in conventional radiosonde transmitters: resistances are switched into the blocking-oscillator grid circuit. In the case of pressure or ballast-count, fixed resistors causing distinct blocking frequencies are used; for temperature, the switch introduces the thermistor resistances.

When this transmitter operates at a lower frequency, say 1746 kc, the standard aircraft radio compass can be used to find the direction to the transmitter. No suitable standard equipment for ground direction-finding has been available to the project.

C. Receivers and Recorders Used

For the T-49 and T-69 radiosonde transmitters, standard ground-station equipment was used to receive and record the signal. An appropriate receiver (National 110 for the T-49 and SCR-658 for the T-69) feeds the signal through a frequency meter and into a Friez recorder, model AN/FMQ-1(). With this system, frequencies between 10 and 200 cycles per second can be recorded.

When the Olland-Cycle pressure modulator is used, (see Section VI, A,3) with low-frequency pulses indicating the completion of the pressure or reference circuit, a recorder made by the Brush Development Co. (Model BL 212) replaces the Friez recorder and frequency meter. With the AM-1 transmitter, the usual ground receiver has been the Hammarlund Super-Pro Model SP-400-X. For aircraft operation, an aircraft radio compass such as AN/ARN-7 is used.

D. Batteries Used

To extend the life of the batteries used with the T-49 and T-69 transmitters, experimental packs were developed using both dry and wet cells. A typical "12-hour" dry-cell pack for the T-69 was composed of:

B supply: 135V--1 ea. B90FL (especially assembled for N.Y.U. by Burgess Battery Co.) or 6 ea. Burgess XX30 in series--parallel

A supply: 6V--1 ea. Burgess 2F4 or 2 ea. F4H in parallel

C bias supply: 45V tap of B90FL or XX30 assembly

With an AM-1 transmitter, the input power required is as follows: "B" supply, 270 volts at about 300 milliamperes; main "A" supply, $1\frac{1}{2}$ volts at 600 milliamperes; and a separate "A" supply for the power amplifier, $1\frac{1}{2}$ volts at 200 milliamperes. The battery pack includes 8 Burgess XX45 or Eveready 467 in series--parallel; 2 Burgess 4FH batteries in parallel; and one 4FH, respectively. This pack lasts about 20 hours in flight. Also included in the battery container were batteries for auxiliary functions such as Olland-Cycle or program-switch motors, ballast-control relays, and bring-down mechanisms.

The problem of operating at cold temperature was given much consideration. Special cold temperature batteries were tried with insufficient difference in performance to justify the added expense and difficulty of procurement. In addition, it was felt that mass-production methods and quality control associated with standard dry batteries gave greater assurance of satisfactory performance.

Subsequent measurements made of the temperature inside the transmitter battery pack showed that the temperature can be maintained above -10°C if the transmitter and batteries are housed in a box insulated with one- to two-inch walls of Styrofoam. This insulation is effective even through long nighttime periods when no solar heating is added.

One type of battery tested in flight was a light-weight wet cell (Burgess Type AM) of the "dunk" type, (magnesium + silver chloride). These cells were vacuum-packed to provide indefinite shelf-life. Activated by immersion in water just before release, they were expected to produce a constant voltage over a period of 6 hours to overcome cold temperature effects. Those units used proved to be rather unsatisfactory and subject to erratic behavior. Furthermore the cost of the cells was very great compared with ordinary cells.

E. Radio Direction-Finding

For ground stations, when the balloon-borne transmitter is a T-69, the SCR-658 RDF set has been used. With such a set the radio signal can be picked up at distances up to 150 miles and good azimuth bearing may be obtained (accurate to less than one degree). Although the elevation angle may be obtained with equal accuracy when free from distortion, angles of less than 13 degrees are usually affected by ground reflection to such an extent as to render them valueless.

To extend the range over which such sets were effective, two or more usually were used, positioned along the expected track of the balloon at intervals of about 100 miles. With two sets giving crossed azimuth "fixes" the position may be determined. If the elevation angle is above 13 degrees, it is possible to fix the balloon with one SCR-658 (assuming the pressure altitude is known).

For details of the maintenance and use of the SCR-658, see War Department publication T.M. 11-1158A.

When aircraft are used to follow and position the balloon, the use of a radio-compass is found to be feasible, using the AM-1 transmitter at a frequency that is within the limits of the compass receiver. By homing on the signal and flying along the indicated bearing until the compass needle reverses, the balloon's position may be found from initial distances of up to 500 miles. No appreciable cone of silence has been observed in recent flights which used a transmitter operating at 1746 kc.

Radio compass equipment, AN/ARN-7, is described in U. S. A. A. F. publication T. O. 68-10.

F. Radar and Optical Tracking

Because of their limited range, ground radar sets and theodolites were only of minor value in tracking balloons. Sets such as the SCR-584, the SPM-1, and MPS-6 are suggested when the balloon is expected to remain within the 60 to 80 mile range.

VI. INSTRUMENTATION

A. Altitude Determination

To provide accurate, sensitive and readable records of the pressure (altitude) encountered by the balloon, various systems have been tried. A modified radiosonde-type aneroid pressure capsule (Signal Corps ML 310-/) has been the basic sensing element, but three different systems of modulation of the radio signal as a function of pressure have been used.

(1) Standard Diamond-Hinman Radiosonde Pressure Modulator

Seen in Figure 29, the standard Diamond-Hinman radiosonde system provided first pressure sensor used. As the pen arm is pushed

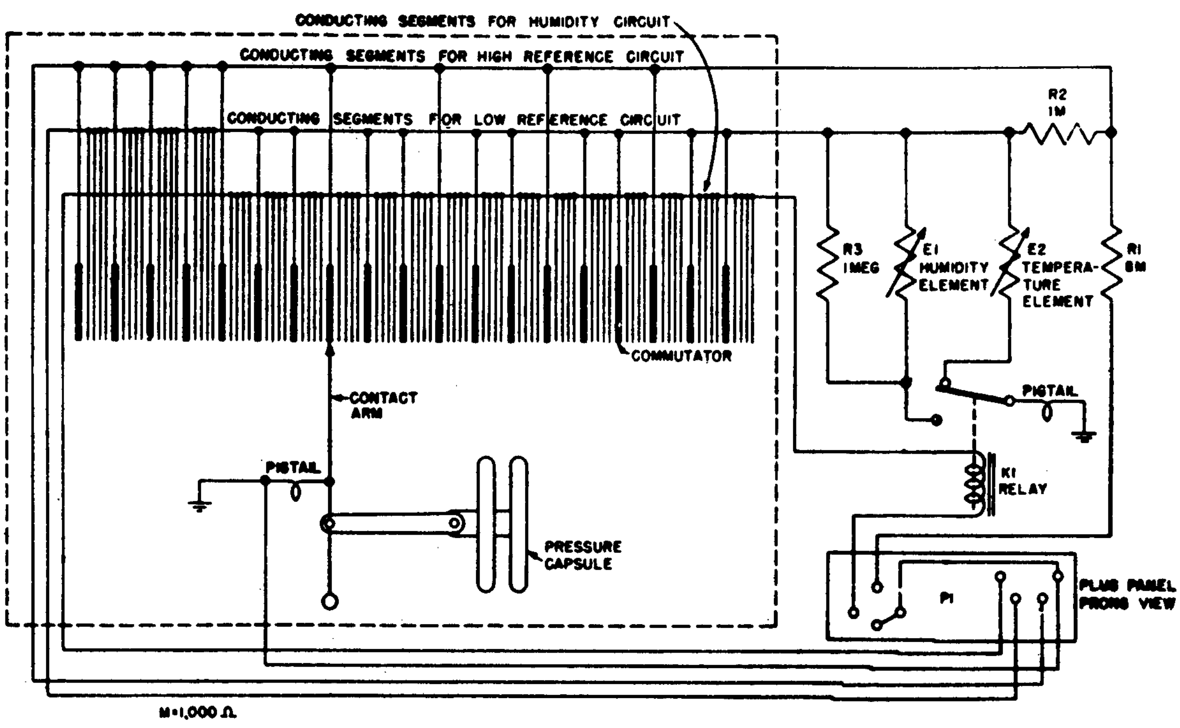


Figure 29. Schematic diagram, Diamond-Hinman radiosonde system.

across the commutator by the aneroid capsule, it falls on alternating insulators and conductors attached to three circuits.

By knowing the altitude of release and counting the number of switches from conductor to insulator, the position along the the commutator is known. This in turn is calibrated to give pressure values, from which the altitude may be computed.

This system was not suitable for floating balloons because (1) only 70 to 90 discrete contacts are provided to cover the entire atmospheric pressure range; this means that the best readability obtainable with this system is about ±10 millibars. (2) When the balloon oscillates about a floating level, the frequent changes from one contact to another give ambiguous readings, since the number of discrete resistances used is limited.

For circuit details of this unit, see T.B. Sig. 165 and the Weather Equipment Technician's Manual.

(2) Specially Coded Radiosonde Modulators

To remove the ambiguity of altitudes reported by the system above, extra resistances were introduced into the circuits of those contacts near the floating level; thus, each contact gives a distinctive frequency and each pressure (altitude) can be clearly distinguished.

In this system, there still remains the lack of resolution or sensitivity inherent in the modulator with 70 to 90 contacts.

(3) Olland-Cycle Modulator

To improve the sensitivity of the pressure measurements, an Olland-Cycle (chronometric) pressure modulator was developed. Seen in Figure 30, the modulator contains a standard Signal

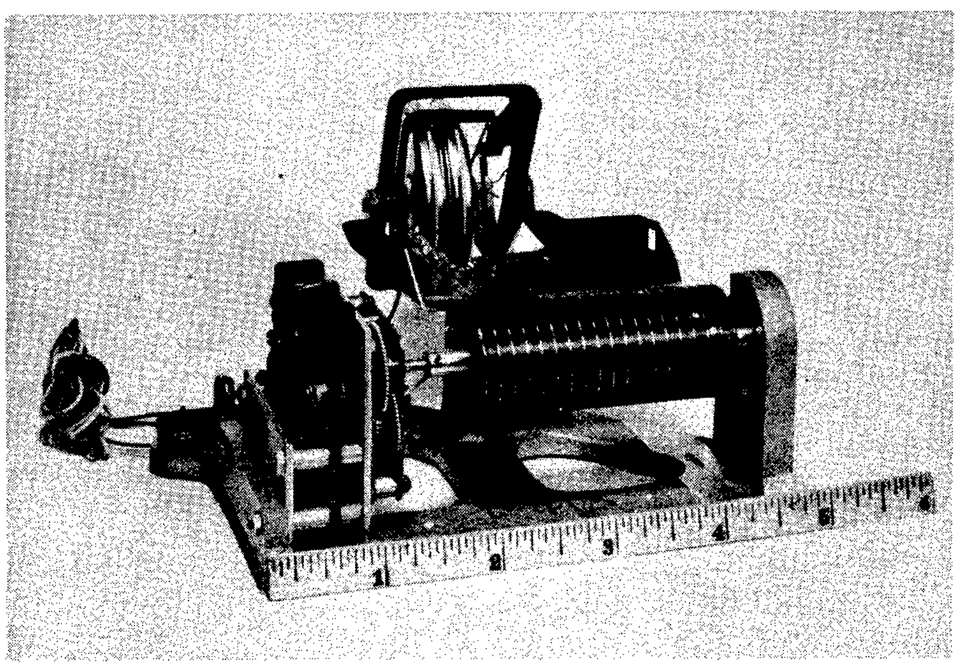


Figure 30. Olland-Cycle pressure modulator.

Corps ML-310/ radiosonde aneroid unit, a metal helix on a rotating cylinder of insulating material, and a 6-volt electric motor which rotates the cylinder.

There are two contacting pens which ride on the cylinder and complete the modulator circuit of the transmitter when they touch the helix. One pen is fixed in position and makes a contact at the same time in each revolution of the helix. This contact is used as a reference point for measuring the speed of rotation of the cylinder. The time that the second pen (which is linked directly to the aneroid cell) makes contact with the spiral, is dependent on the cylinder speed and on the pen position which is determined by the pressure. By an evaluation chart, the atmospheric pressure can be determined as a function of the relative position of the pressure contact as compared to the reference, thus eliminating all rotation effects except short-term motor speed fluctuations.

The operation of this unit is described in detail in Section II, "Operations," of this report, pages 54-63.

Some of the units flown have been made in the shops of the project, while others have been commercially supplied. The following specifications have been set up for performance of the Olland-Cycle:

> Pressure range: 1050 to 5 mb.
> Temperature range: +30°C to -30°C
> Accuracy: ±0.2 mb.
> Readability: ±0.1 mb.

A number of tests have been made on the accuracy of the Olland-Cycle modulator. The tests were of two types. The first was made running the unit at room temperature while the pressure remained constant. In the second, the pressure was varied from surface pressure to about 20 millibars several times at different temperatures. In tests of the first type, the maximum variation of pressure for a given contact pen position was 1.3 millibars in a series of 182 revolutions.

The most comprehensive tests of this type were made with two Olland-Cycles in the same bell jar running for three hours and ten minutes. Due to differences in speed of revolution, different numbers of revolutions were recorded in the time interval, 138 being made by instrument No. L-416 and 181 by instrument No. B-501. No. L-416 was made in the shops of the Research Division and used a Brailsford 6-volt (1 rpm nominal speed) motor, hard-rubber cylinder with 8 turns per inch of .010" nickel wire on a ¼" aluminum plate base. No. B-501 was made by Brailsford and Co. to Balloon Project specifications. It had the same 6-volt motor, a paper base bakelite cylinder with 8 turns per inch of .010" nickel wire and was mounted on a 1/16" sheet aluminum frame.

The following statistics for a given pressure (1001.8 millibars) were computed:

	N.Y.U. Shop Model L-416	Brailsford Model B-501
on the mean	12.5%	34 %
within 0.1% of mean	25 %	50 %
" 0.2% " "	41.5%	70.5%
" 0.3% " "	62.5%	85.5%
" 0.4% " "	75 %	91 %
" 0.5% " "	95.6%	100 %

Other conclusions arrived at as a result of this test were:

(a) Since changes of speed of the motors did not occur simultaneously in the two instruments, the speed changes probably are not due to slight changes in pressure or temperature.

(b) Sensitivity varied from 0.1 to 0.9 millibars.

(c) Sensitivity increased with increase of rate of pressure change.

It was recommended as a result of these tests that the records of flights when the balloon is floating be read to the nearest two-tenths of a percent of a cycle, or approximately two-tenths of a millibar, for high accuracy. When using the instruments manufactured by Brailsford and Co., satisfactory accuracy will be attained, if necessary, when the record is read to the nearest one-tenth of a percent of a cycle.

In the second group of tests the pressure was reduced slowly to about 20 millibars and increased to sea-level pressure at different temperatures.

The most comprehensive series of calibrations was made with the first instrument made by Brailsford and Co. Two runs were made at room temperature (22°C), one at -10°C, one at -30 to 37°C and one at -56 to -62°C. On the last test at the lowest temperature, the unit was found to be completely unreliable. The cause of failure was the erratic motor operation at extremely low temperatures. This had been observed previously during flights when the Olland-Cycle was not thermally insulated.

The other curves were plotted on a single chart in order to study their spread (see Figure 31). The envelope of curves thus obtained showed no regular temperature effect over the range +22°C to -37°C. In general, the envelope was less than 10 millibars wide although at some higher pressures it was as much as 12 millibars wide. The curves at low pressures fell closest together and were all within 3 to 4 millibars apart between 50 and 150 millibars and 6 millibars apart between 150 to 200 millibars.

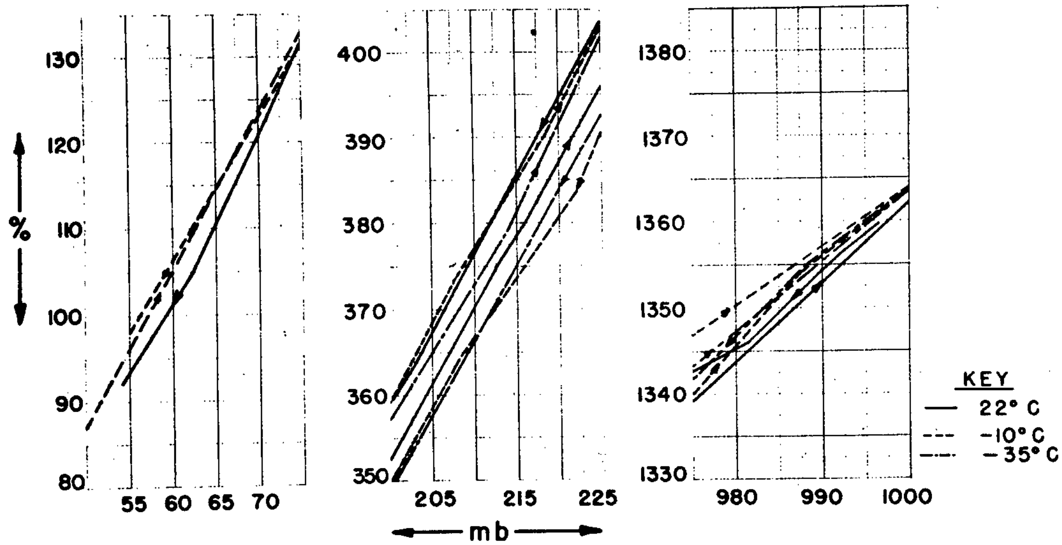


Figure 31. Tests of Olland-Cycle performance.

Hysteresis at any one temperature was the worst serious cause of the width of the envelope of curves. However, this error was minimized by the smoothness of the rotating cylinder and the continuous motion of the cylinder under the contact pen. Probably the necessary looseness of the bearings and the joining to the motor gear train had a great deal to do with the spread between different calibrations.

The maximum variation of any one calibration curve from the mean was about ±3 millibars.

The following recommendations are made for the use of the Olland-Cycle modulator:

(a) The modulator should be mounted inside the battery box and insulated so as to keep its temperature above -30°C.

(b) During the rapid-rising portion of the flight the accuracy of the data warrants reading only to the nearest one percent of a cycle, or about one millibar of pressure.

Tests on the sensitivity of Olland-Cycle modulators indicate that although the accuracy is limited as indicated above, small variations may be detected with the result that it is valid to read the pressure record to the nearest tenth of one percent of one revolution.

When the Olland-Cycle principle was originally adopted, both clocks and electric motors were considered for the power supply. In addition to the tendency of clocks to stop at cold temperatures due to freezing of lubricants and unequal expansion of the parts, the movement of the clockwork in discrete steps limits the accuracy of sampling. For these reasons, electric motors are preferred.

The motor now in use has been built to meet the following specifications:

(a) 6 to 7.5 volt operation.

(b) 1 RPM gear train.

(c) 20 to 40 milliamperes drain.

(d) Speed change at low temperature to be no more than 20%.

(e) Constancy of speed during any single revolution not to deviate by more than 0.3%.

To check the performance of these motors at cold temperatures, a series of testswas run on the motors now in use with the average case seen in Figure 32. The loss in RPM was more than

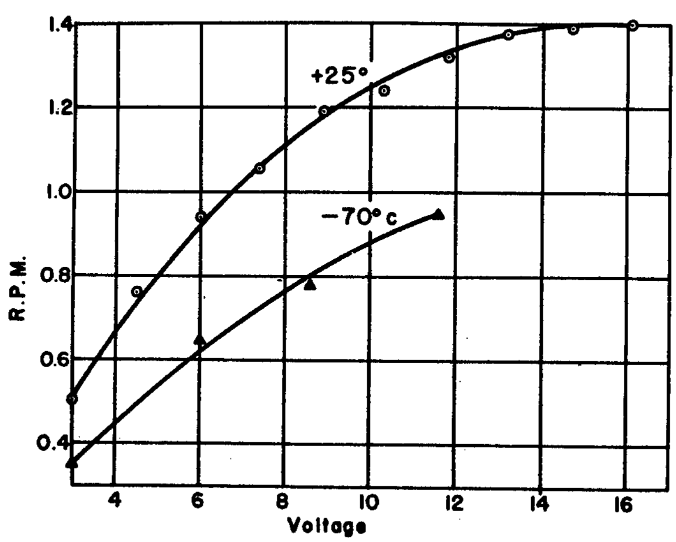


Figure 32. Speed tests of Olland-Cycle motors.

desired, but the motors continued to operate at a steady rate. As long as the speed of revolution does not vary markedly within a single revolution, the error is not serious. In early flights made at prolonged cold temperature, erratic performance of the motor-driven units was observed; current practice is to provide adequate temperature insulation.

(4) Barograph

As a secondary pressure unit, a clock-driven barograph has been included on many flights. The instrument (shown in Figure 33)

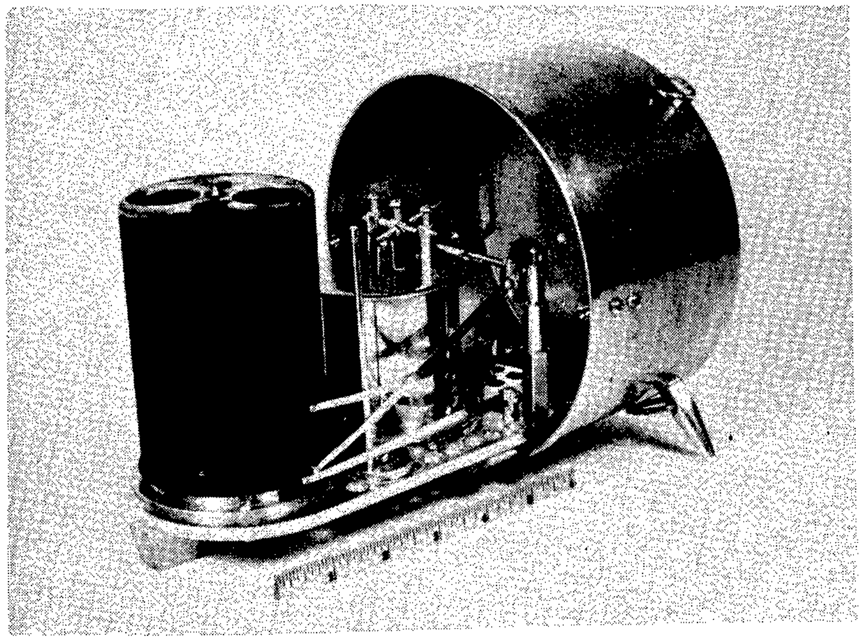


Figure 33. Smoked drum barograph.

will provide up to 40 hours of pressure data if recovered. About 70% of all those units flown to date have been recovered. The performance specifications are as follows:

(a) Rotation: one revolution every 12 hours

(b) Duration: 36 hours running time

(c) Pressure range: 500 to 5 mb.

(d) Accuracy: ±5 mb.

(e) Readability: 1.0 mb. or approximately .22 mm on the drum

(f) Weight: 1000 grams

(g) Time accuracy: 10%

(h) Temperature compensation between 30°C and -70°C

Instruments have been built by Lange Laboratories to meet these requirements (the time accuracy figure is questionable).

A description of the use of this barograph is given in Part II, "Operations," of this report.

B. Temperature Measurement

To interpret some of the observed balloon behavior, a knowledge of the temperature of the gas and the outside air temperature was required. The evaluation of "superheat" effects was accomplished primarily by exposing a conventional radiosonde thermistor inside the balloon with a control thermistor measuring the free-air temperature. Similarly, a thermistor was sometimes installed inside the battery-pack housing to measure the temperature of the batteries.

While this system was in use it was general practice to use the standard government service thermistors ML 376/AM (brown) and ML 395/FMQ-1 (white). The white elements were needed when the external temperature was measured, since no adequate protection from the sun was available. Also, at floating level there is no ventilation to be had since the balloon is stationary with respect to the air.

The resistance of the thermistors was switched into the grid circuit of the blocking oscillator of the AM-1 transmitter, and by comparison with pre-flight calibrations the audio frequency transmitted could be interpreted in terms of temperature. To record the signal after it was received, a fast-speed Brush Co. Oscillograph Model BL212 is used. (Due to the frequency response of the Brush recording system, the circuit was arranged to give lower frequencies than a standard radiosonde for the same temperature range.) A sample calibration chart is shown in Figure 34.

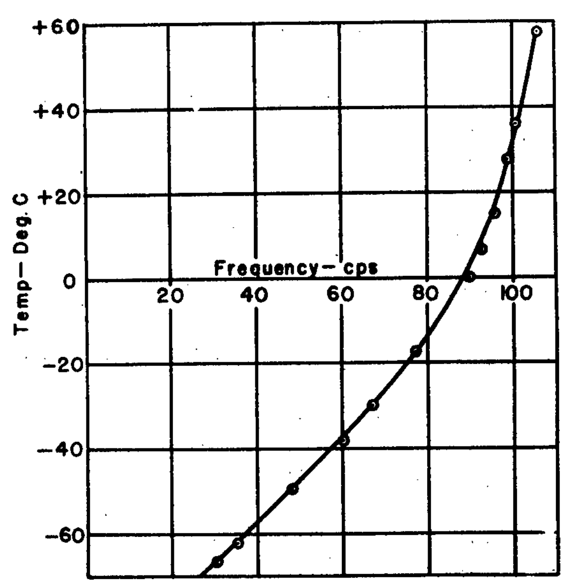


Figure 34. Sample calibration chart for temperature measurements.

The temperature data obtained was of considerable value, especially to determine the effect of insulation of the battery pack. It was found on most flights where reasonable thermal insulation was applied that the temperature of the pack remained above 0°C after several hours of exposure at nighttime. The extreme observed was -10°C. Daytime flights had the added advantage of heating from the sun.

The temperature of the lifting gas at the ground was ordinarily found to be somewhat below the temperature of the air. This is due to the extreme cooling encountered in the expansion of the compressed gas as it was fed from the tanks into the balloon. During the rising period, in daytime, the gas gained heat, since it cools adiabatically less rapidly than does air (also less than the normal tropospheric lapse rate); at the floating level a differential of about 10°C was common. A typical temperature trace is shown in Figure 35.

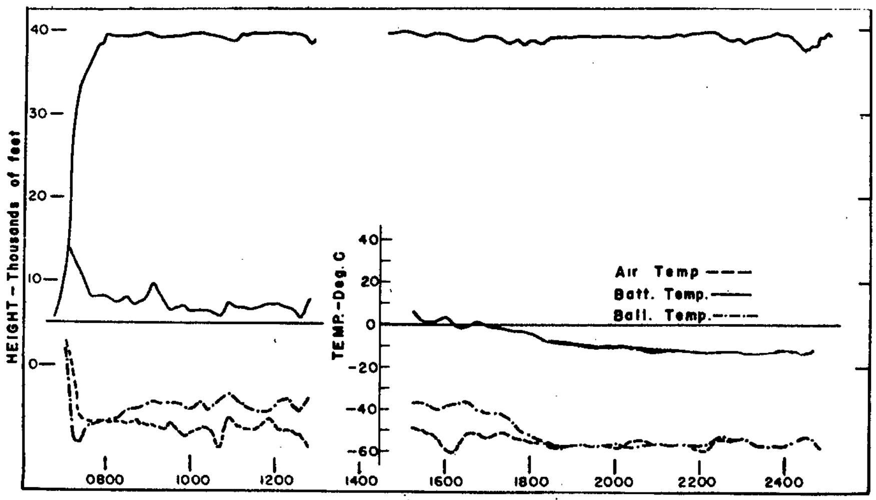


Figure 35. Typical temperature record.

To permit the transmission of both temperature and pressure data by one radio channel, a pair of programming switches have been designed and flight tested. The first is the temperature switch (Figure 36),

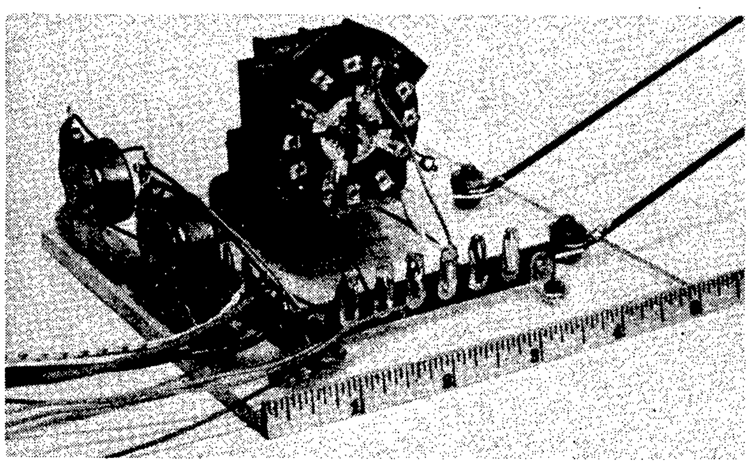


Figure 36. Temperature programming switch.

which switches four elements into the transmitter circuit in turn. Recently a motor making five revolutions per minute was used so that each temperature is transmitted for three seconds. The four elements are the free-air temperature, the gas temperature, battery-pack temperature and a reference signal. This switch is supplemented by a master program switch which alternately places the temperature switch and the pressure modulator into the transmitter circuit. The present arrangement is to permit the temperature data to be transmitted for about one minute in every fifteen. In this way representative temperature sampling may be obtained, without materially destroying the continuity of the pressure and ballast data.

A second system of determining temperature makes use of the smoked drum of the barograph. By adding a temperature-activated pen, this unit makes a record of the temperature encountered. Since it is not the free-air temperature nor the temperature of the lifting gas but rather the temperature of the barograph itself, the data obtained has been of little value. Following the development of suitable temperature telemetering apparatus, this method was not used.

C. Ballast Metering

It is often very desirable to know whether or not ballast control equipment is operating properly during flight tests. For this purpose, two systems of ballast metering have been devised. It is possible (1) to record on an instrument which is balloon-borne or (2) to detect and telemeter information to the ground concerning ballast flow.

Figure 37 shows the automatic siphon which has been used in the AM-1 transmitter circuit for the telemetering of such information. A series of pulses of fixed frequency is transmitted whenever the contact arm of the automatic siphon is filled above a critical level. The electrolyte used is non-miscible with the ballast and rises and falls in proportion to the rise and fall of the main arm of the siphon. This main arm empties when approximately 3.5 grams of ballast have been allowed to flow into it. As a consequence of this intermittent filling and emptying of the lines of the siphon, an intermittent signal of fixed frequency is transmitted whenever ballast is flowing steadily. It is important that an electrolyte be used which will not freeze at low atmospheric temperatures and will not boil at the low pressures encountered. After a series of tests it was decided that a 24% solution of hydrochloric acid be used for altitudes up to 85,000 feet. It is necessary to use platinum wire for the contact points.

In order to record in flight the functioning of the ballast control system a ballast recording mechanism has been developed in conjunction with the Lange Laboratories of Lexington, Kentucky. This

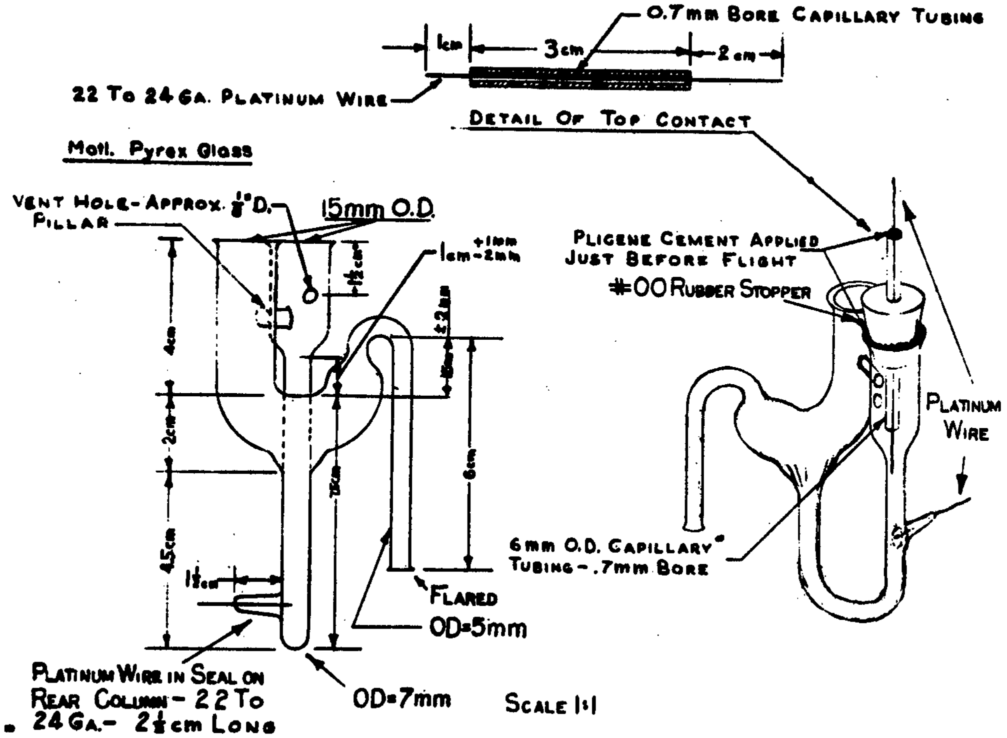


Figure 37. Automatic siphon.

instrument has been added as a part of the baro-thermograph. A cutaway sketch of this ballast-recording instrument is shown as Figure 38.

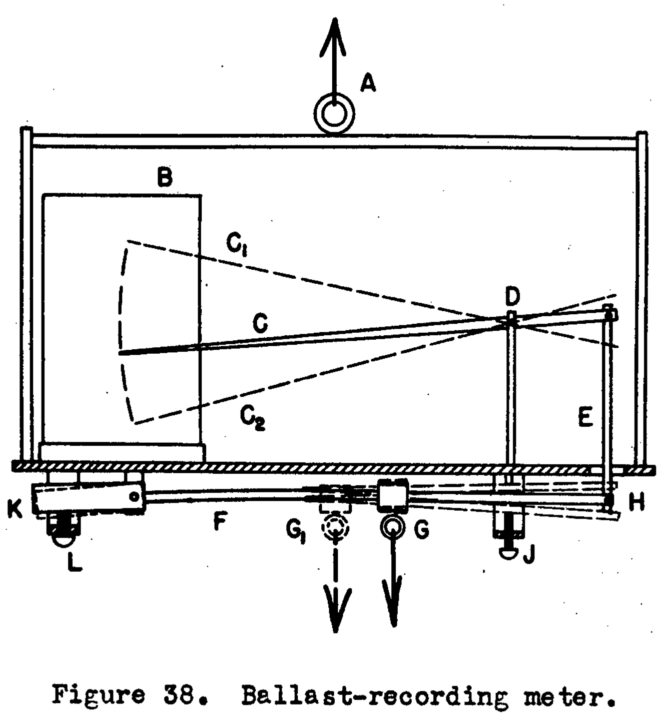


Figure 38. Ballast-recording meter.

Operation of the instrument may be described as follows: The instrument is inserted in the load line just above the ballast assembly by attaching the load line to the upper ring (A) and the rigging from the ballast assembly to the lower ring (B). A cantilever spring (F) is set into an adjustable base (K), which may be adjusted for various empty ballast-assembly weights by changing the setting of the adjusting screw (L). The lower ring is attached to the cantilever spring, but can be adjusted for different ballast weights by sliding along the spring (from G to G_1, for instance). For light ballast weights the lower ring is moved away from the base (K) (to the right on the diagram), and for heavy ballast weights it is moved toward the base. Adjustments are made on the adjusting screw (L) and the lower ring (G) before each flight according to the weights of the ballast assembly and the ballast.

The cantilever spring is attached to the connecting bar (E) at (H). Thus the deflection of the lower ring is transferred through the cantilever spring to the connecting bar and then to the pen arm (C), which is pivoted about a fixed point (D). The deflection is recorded by the pen on a rotating smoked drum (B). In order to prevent the pen from going off the drum, an adjustable stop is set at (J).

The unit should be calibrated for maximum load (pen arm at C_1), a medium load (pen arm at C) and minimum load (pen arm at C_2) before each flight. A trace of ballast function will start at the top of the drum and as ballast is discarded will fall toward the bottom of the drum. By measuring the deflection at any time and comparing with the calibration, the amount of ballast left in the assembly at any time can be determined. Since this instrument is a part of the baro-thermograph, the trace obtained upon recovery will contain information concerning altitude, temperature, and ballast functioning over the complete flight. After proper correction for time displacement of the three pens has been made, the three types of information can be correlated to give a fairly complete picture of the balloon flight, including reasons for various types of motion.

It is expected that this instrument will be extremely valuable in determining ballast control operation over a long period of time, especially after the balloon system is out of radio reception range. It also will give information that could not be obtained if there were any failure of the automatic siphon meter or the transmitter during launching or flight. The chief drawback of the instrument is that information is dependent on recovery.

At the time of writing of this report the instrument has not been flight tested. Preliminary laboratory tests indicate that the instrument will live up to the high expectations placed upon it. Since the instrument actually records the tensile force in the load line during flight, it may also be valuable in analysis of the acceleration forces induced during periods of balloon oscillation in the atmosphere.

VII. CONCLUSIONS

Considerable experimental work has been done in conjunction with the study of balloons and controls. The description of operating procedures and the use of specially developed equipment is included in Part II of this report, "Operations," (bound separately).

A summary of the results of flights made to test equipment and controls is given in Part III, "Summary of Flights." At this time the use of thin polyethylene balloons with pressure-activated ballast controls has been demonstrated effectively to meet the contract requirements. Tests made on another contract have found controls consistently active over 24 hours with an average pressure constancy of ±2 mb. at 200 mb. Even greater ballast efficiency has been found at higher altitudes using the same pressure-activated controls.